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ON THE THEORY OF DISTURBANCES IN A CONDITIONALLY UNSTABLE ATMOSPHERE

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ABSTRACT

A perturbation model is developed which is applicable to small-amplitude moist convective disturbances of scales ranging from those of squall lines to tropical cyclones. In an extension of the works of Syōno and Haque, disturbance development is studied for an atmosphere in which static stability may vary with height and with the sense of the vertical motion, being in general negative for upward motion in some substantial layer. Closed solutions for simplified cases are exhibited as well as results of numerical integration of a more realistic case. The dynamic stability criterion depends on the static stabilities in the ascending and descending currents and their dimensions and geometric relationships. Cloud-scale and meso-scale disturbances are more unstable than those of cyclone-scale, and presence of the former may tend to destroy conditions favoring development of the latter. Evaluation is made of the linearized effects of parallel convective bands, an "eye", the tropopause, nonhydrostatic motions, surface friction, and various boundary conditions. Comparison of solutions with observational features shows fair agreement in some respects, improving considerably when nonlinear effects are qualitatively considered. The disturbances are effective in transporting kinetic and potential energy outward from the actively unstable updraft. Nonlinear interactions tend to transport heat upward to modify the initial static stability distribution. A second-order dynamic stability criterion, obtained by consideration of nonlinear effects, tends to favor development of an existing finite-amplitude disturbance of tropical cyclone scale.

1. INTRODUCTION

One of the most successful mathematical tools for the study and elucidation of meteorological phenomena has been the linearized perturbation model. Our present understanding of synoptic-scale motions in the troposphere is, in fact, strongly dependent upon studies of linearized barotropic and baroclinic motions and these also have been necessary prerequisites to construction of useful nonlinear forecasting models. In light of this background it would seem that the study of linearized moist convection might provide a useful background to attempts at dynamical forecasts for regions and scales of motion for which such phenomena are important.

"Dry" convective motions, i.e., those involving no changes of phase, have been studied theoretically and observationally for many years. Results of linear theory—the stability criterion including the effects of scale, symmetry, and the fluid parameters—have been fairly well verified in the special cases where the assumptions of the theory hold. The importance and complexity of the phenomenon are such that it still provides a fertile field for investigation, particularly in regard to nonlinear effects. It seems likely, however, that many important forms of atmospheric convection cannot be considered as special cases of Bénard cellular convection. In particular, the largest important form of direct convective circulation, the tropical cyclone, develops in considerable contradic-

tion to the scale selectivity results of Bénard cell theory. While this contradiction has never been adequately resolved, it is perhaps generally agreed that consideration of condensation effects is indispensable to its satisfactory explanation.

In recent years two authors have considered linear solutions of a complete nonviscous set of hydrodynamic equations with inclusion of condensation effects; in both cases the results were applied principally to tropical cyclogenesis. Syōno [21] considered a frictionless quasi-static system with static stability negative for all vertical motions, and allowing a certain very restrictive form of basic flow obtained solutions similar to those of type I of this investigation. Haque [8] considered motions on a basic rest state, but allowed the static stability to change sign with the sense of the vertical motion, to approximate the effects of moist updraft and dry downdraft. He also used the nonhydrostatic vertical equation of motion and considered the effects of an "eye" and (somewhat erroneously) the tropopause. In both these studies there were certain deficiencies in the physical interpretation of the results. In particular, no evident attempt was made to reconcile the stability criterion, which indicated complete dominance of cloud-scale systems, with the actual existence and growth of disturbances of much greater time and space scales. There was no consideration given to the possibility of line-symmetric disturbances, or of circular convective bands about a center. Finally the energy transports and transformations were not discussed and no mention was made of nonlinear effects, even as to orders of magnitude.

This study may be considered to be, in large part, an extension of the results of Syōno and Haque in an attempt to rectify the deficiencies mentioned above, and to include as well cursory investigations of the effects of surface friction, some variation of boundary conditions, and realistic distribution of static stability for both moist and dry processes. It appears that there is also some applicability of linear methods to meso-scale convection; e.g., that of cloud bands, as distinguished from individual cloud cells. It was therefore considered desirable to develop some cases pertaining to meso-scale motions and their interrelation with those of larger scale.

A further purpose of this study should be mentioned, one which has particular significance to the field of numerical weather forecasting. Recent results of Phillips [19] and Smagorinsky [20] lead to the conclusion that a forecast scheme using the primitive equations of motion is practical and in several respects more satisfactory for prediction of baroclinic motions than schemes using derived equations. If such a scheme is used in a model in which moisture and its thermodynamic effects are included explicitly and static stability is self-determined, then one may anticipate the occasional development of conditionally unstable inertio-gravitational motions, which may grow to large amplitudes unless suppressed by some more-or-less arbitrary method. The conclusions of this study indicate that meso-scale and cloud-scale convections are generally sufficient physical mechanisms for release of this instability. Under certain special initial conditions, however, larger scale motions may develop, whose dimensions are determined by both the linear and nonlinear terms of the dynamic equations.

2. PLAN OF INVESTIGATION

As stated in the introduction, the principal results of this study will be obtained by use of the linearized atmospheric equations. The effects of nonlinear terms will, however, be considered in assessing the results and validity of the linear theory and for obtaining second-order corrections to these results. The variation of Coriolis parameter with latitude and the possible existence of a nonuniform basic flow will be ignored, as well as the effects of nonuniform orography. It is found possible, however, to investigate some of the effects of surface friction, the tropopause, and acceleration terms in the vertical equation of motion. Some of the most significant results of this investigation are found upon consideration of moist convective elements surrounded by or scattered through a nonsaturated air mass.

The investigation proceeds as follows: The basic linear nonviscous differential equations in the p-coordinate system are reduced to a single fourth-order partial differential equation with ω as the dependent variable. Boundary and initial conditions are constructed from appropriate physical considerations. Eigenfunction solutions are obtained in time, space, and pressure for varying specifications of hydrostatic stability and boundary conditions. Eigenvalue considerations lead to a wave equation relating the horizontal and vertical disturbance scale parameters, hydrostatic stability, and rate of disturbance growth. The wave equation is investigated to clarify the relationship of the factors determining growth rate. Corrections to the wave equation for nonhydrostatic terms in the vertical equation of motion are discussed and the close relationship of the solutions to internal gravitational waves is pointed out.

The energy transformation and transport terms are next considered, and special attention is paid to the transfer of energy from active (moist) regions to adjoining passive (dry) regions.

Finally we investigate the nonlinear terms arising when the linear solutions are substituted into the complete meteorological equations, in order to determine the validity of the perturbation approach, to show the changes in the form of the disturbance and in the stability criterion produced by nonlinear terms, and to indicate effects of the disturbances upon their environment.

3. DIFFERENTIAL EQUATIONS AND BOUNDARY CONDITIONS

The linearized nonviscous quasi-static equations of atmospheric motion, continuity, and heat may be written

with pressure as the vertical coordinate (see Eliassen [4]) as follows, where perturbations were assumed on a basic barotropic rest state:

$$\frac{\partial \mathbf{V}}{\partial t}+f\mathbf{k}\times\mathbf{V}+\nabla\Phi=0 \tag{1}$$

$$\frac{\partial \Phi}{\partial p}+\alpha=0 \tag{2}$$

$$\nabla\cdot\mathbf{V}+\frac{\partial \omega}{\partial p}=0 \tag{3}$$

$$\frac{\partial \alpha}{\partial t}-\sigma\omega=0 \tag{4}$$

where $\mathbf{V}$ is the horizontal velocity, Φ the geopotential, α the specific volume, and $\omega=dp/dt$, the quantity analogous to vertical motion. The Coriolis parameter f is assumed constant and the static stability analog $\sigma=-(\partial\overline{\alpha}/\partial p+\overline{\alpha}/\kappa p)$ is a function of the space variables only, where κ is a polytropic coefficient, equal to c_p/c_v in the case of dry motions. This set is reduced to a single equation in ω by the elimination of variables as follows: Equation (1) is operated upon successively by the horizontal divergence and vertical curl component operators and the vorticity eliminated between the two resulting equations to yield an equation in divergence and Φ. Divergence is eliminated in favor of vertical velocity by (3), and the result combined with (2) and (4) to eliminate α and Φ and obtain the desired equation in ω.

$$\left(\frac{\partial^2}{\partial t^2}+f^2\right)\frac{\partial^2\omega}{\partial p^2}+\nabla^2(\sigma\omega)=0\cdot \tag{5}$$

The stability factor σ is the most important determinant of both the physical and mathematical features of equation (5). By use of the hydrostatic equation and the equation of state we can represent this parameter as follows:

$$\sigma=-\frac{\overline{\alpha}}{\overline{T}}\left(\frac{\partial\overline{T}}{\partial p}-\frac{\kappa-1}{\kappa}\frac{\overline{T}}{p}\right)=\frac{\overline{\alpha}}{p}\frac{\gamma_{ad}-\gamma}{\gamma_{ac}} \tag{6}$$

where $\gamma_{ad}=\frac{g}{R}\frac{\kappa-1}{\kappa}$, the dry or moist adiabatic lapse rate, $\gamma_{ac}=g/R$, the autoconvective lapse rate, and $\gamma=-\partial\overline{T}/\partial z$, the actual atmospheric lapse rate. Values of σ for both dry and moist motions have been calculated from virtual temperatures for the mean hurricane season tropical atmosphere recently published by Jordan [12], and are given in table 1, where σ_d is the dry and σ_w the moist stability.

At levels above the tropopause, where $\overline{T}\approx$ constant, equation (6) shows that:

$$\sigma\approx\frac{R\overline{T}}{p^2}\frac{\gamma_{ad}}{\gamma_{ac}}\approx\frac{R^2\overline{T}}{c_p p^2} \tag{7}$$

and therefore $1/\sigma\rightarrow 0$ as p^2.

The top and bottom boundary conditions for solutions of (5) required by physical considerations are, respectively

$$\omega=0 \text{ at } p=0 \tag{8}$$

$$w=0 \text{ at } z=0 \tag{9}$$

where w is the vertical velocity.

Expansion and linearization of the second of these give the form

$$\frac{\partial\Phi}{\partial t}+\overline{\alpha}\omega=0 \text{ at } z=0. \tag{10}$$

The surface $z=0$ corresponds approximately to the pressure surface $p=p_0+\Phi(p_0)/\overline{\alpha}(p_0)$. By analogy with the simple treatment of waves on a fluid surface, however, we assume (10) to apply to a pressure surface, so that

$$\frac{\partial\Phi}{\partial t}+\overline{\alpha}\omega=0 \text{ at } p=p_0. \tag{11}$$

A further simplification, which will be shown to introduce little error in solutions of the types considered in this study, consists of neglect of the first term of (11), reducing it to the form:

$$\omega=0 \text{ at } p=p_0. \tag{12}$$

The latter is known in numerical forecasting to be a filtering condition for elimination of external gravitational waves (Hollman [10]).

For consideration of the effects of a tropopause it will be shown that (8) may be effectively applied at a pressure level p_H, where p_H is slightly less than p_T, the tropopause pressure.

The effects of surface friction are accounted for, rather crudely, by assuming a forced vertical motion at the top of the friction layer, proportional to the geostrophic vorticity, that is

$$\omega=B\left(\frac{p_F-p_0}{f}\right)\nabla^2\Phi \text{ at } p=p_F\approx 900 \text{ mb.} \tag{13}$$

where B is a nondimensional coefficient, perhaps a function of scale. Assuming an Ekman spiral velocity profile in the friction layer, Charney and Eliassen [3] have

TABLE 1.—Values of dry and moist static stability for the mean hurricane season tropical atmosphere

Pressure (mb.)	σ_d (10^{-3}m.^{2}mb.$^{-2}$ sec.$^{-2}$)	σ_w (10^{-3}m.^{2}mb.$^{-2}$ sec.$^{-2}$)
950	6.04	−9.96
900	9.24	−8.00
850	12.95	−5.81
800	14.85	−5.54
750	16.87	−5.40
700	18.26	−6.04
650	20.7	−6.58
600	24.6	−5.31
550	28.2	−4.06
500	32.0	−2.32
450	36.7	−1.30
400	39.0	4.02
350	39.3	8.17
300	42.1	17.92
250	43.3	30.3
200	104.2	96.9
175	164.	159.
150	344.	341.
125	788.	784.
100	1837.	1837.

shown that $B=(\sin 2\psi)/2$, where ψ is the indraft angle at the surface. The Ekman spiral, however, is not commonly observed in the subcloud layer over the tropical oceans. It turns out that we do not need to know B exactly, but only its sign and general order of magnitude. We assume, therefore that $|B|<1$ and that B is positive for large scales of motion and negative for small scales (where friction opposes the normal indraft).

As to external lateral boundary conditions, in most cases we consider the atmosphere to be horizontally infinite, so that the only requirement is that the dependent variables remain finite over all space. In the one case in which lateral limitations are used, it is assumed that the velocity normal to the boundary vanishes.

It will later be shown that meaningful solutions of (5) exist for which the static stability parameter, σ, may be discontinuous in the horizontal and/or vertical. At the discontinuities the differential equations involving σ are inapplicable and must be replaced by internal boundary conditions. We assume that these conditions consist of the continuity of Φ (dynamic condition) and the normal wind component (kinematic condition) across the boundary. Thus for a vertical internal boundary (σ discontinuous horizontally)

$$\left.\begin{aligned} v_n^{(1)}&=v_n^{(2)}\\ \Phi^{(1)}&=\Phi^{(2)}\end{aligned}\right\} \tag{14}$$

where v_n is the wind component normal to the boundary, or for a horizontal boundary

$$\left.\begin{aligned} \omega^{(1)}&=\omega^{(2)}\\ \Phi^{(1)}&=\Phi^{(2)}\end{aligned}\right\} \tag{15}$$

The superscripts (1) and (2) refer to opposite sides of the boundary.

Since $\overline{\alpha}$, and therefore σ, is not a function of time, a separable time solution may be assumed, consisting of positive and negative exponent terms. We are interested in unstable waves, and we therefore ignore the negative exponential and write,

$$\omega=e^{qt}\Omega(x,y,p) \tag{16}$$

where Ω is the spatial function satisfying the reduced differential equation

$$\nabla^2(\sigma\Omega)+(f^2+q^2)\frac{\partial^2\Omega}{\partial p^2}=0. \tag{17}$$

Inspection of table 1 shows that, as is generally known, static stability is negative with respect to the moist adiabatic process in the low levels of the tropical troposphere in summer, but is positive for dry motions. Since the atmosphere in these regions usually contains substantial amounts of moisture it is frequently only a small exaggeration to say that all upward motion proceeds at the unstable moist adiabatic lapse rate and all downward motion at the stable dry rate. If then, we equate saturated cloudy regions with negative values of σ (and ω) and dry clear regions with positive σ (and ω), equation (17) becomes a mixed elliptic-hyperbolic type equation with an internal boundary condition. The general theory of such systems is far from well established, although they are frequently encountered in the study of transonic flow (see, e.g., Frankl [5]). No method has been devised for obtaining an analytic or numerical solution of the system with realistic values of σ in both the moist and dry regions. It is relatively simple, however, to obtain solutions for σ constant or a variable function of only one coordinate. In this way we may qualitatively approach the results of a solution of the physically realistic system by considering three general types of solution, corresponding to three approximations to the true stability function.

Type I solutions are obtained for σ equal to a constant. The system here is similar to that used by Syōno and yields results, in particular the dynamic stability criterion, which set a standard of comparison for more complicated cases. For type II we allow σ to vary in the horizontal only, being negative in moist regions and positive elsewhere, and we further restrict it and all other quantities to one-dimensional variation. Type III solutions are obtained under the assumption that σ is constant horizontally but variable in the vertical. This allows consideration of the effects of stable layers and the tropopause.

It is possible to obtain simple solutions for a fourth type of stability variation; that is, where σ is a function of pressure multiplied by a function of horizontal space. Such a solution was considered by Haque, but the results are not particularly meaningful. Table 1 shows that σ_w and σ_d are of approximately equal magnitudes and opposite signs in the low levels, but are essentially identical above 200 mb. Thus this fourth type of solution is not a substitute for the presently unobtainable solution for the realistic form of σ.

4. TYPE I SOLUTIONS

For σ equal to a constant, one can immediately separate variables in (17) and obtain the reduced differential equations in the form

$$\frac{d^2P}{dp^2}+\frac{K^2}{p_0^2}P=0 \tag{18}$$

$$\nabla^2(\sigma W)-\frac{f^2+q^2}{p_0^2}K^2W=0 \tag{19}$$

where $\Omega=P(p)\,W\,(x,\,y)$ and $(K/p_0)^2$ is the separation constant. If boundary conditions (8) and (12) are applied to (18), it is found that K is an eigenvalue such that

$$K=n\pi,\qquad n=1,2,\ldots \tag{20}$$

The use of boundary conditions (8) and (11) leads to a somewhat more complicated relation

$$K \tan K = -\sigma p_0/\bar{\alpha}_0. \tag{21}$$

The right-hand side is much smaller than unity, and solutions of (21) may be found by expansion of the left side about the approximate (zero-order) solutions given by (20). To the first order these solutions are

$$K=\begin{cases} (-\sigma p_0/\bar{\alpha}_0)^{1/2}, & n=0 \\ n\pi-\dfrac{\sigma p_0}{n\pi\bar{\alpha}_0}, & n=1, 2, \ldots \end{cases} \tag{22}$$

For $n \geq 1$ the eigenvalues obtained from the more accurate lower boundary condition are essentially unchanged from those of the more approximate case. The solution for $n=0$ represents an external gravity wave which is not of interest in this study. We are therefore justified in using lower boundary condition (12) as sufficiently accurate for the present purposes.

Elementary solutions to (19) may be found in any of several forms, depending on the coordinate system used. For simplicity we choose to specialize the system to one-dimensional variation in either the Cartesian or cylindrical coordinate system with symmetry about the origin and W always finite. Thus W is either an even function of x or a function of r. In either case the coefficient of the second term of (19) must also assume discrete values (eigenvalues) and we may write

$$\nabla^2 W + (k/L)^2 W = 0 \tag{23}$$

where $k=\pi/2$ in the Cartesian case, $k\approx 2.405$ (the first zero of the Bessel function of order zero) in the cylindrical case, and L is the distance from the origin to the point where W first changes sign. The solutions for ω in the Cartesian case are as follows:

$$\omega = Ae^{qt} \sin \frac{n\pi p}{p_0} \cos \frac{kx}{L}, \qquad k=\pi/2. \tag{24}$$

The wave equation may be found as a condition which simultaneously satisfies (19), (20), and (23), that is

$$q^2+f^2=-\left(\frac{p_0/n\pi}{L/k}\right)^2 \sigma. \tag{25}$$

Solutions for Φ, $\mathbf{V}$, and α for the Cartesian case are as follows:

$$\Phi=\frac{p_0\sigma}{n\pi q} Ae^{qt} \cos \frac{n\pi p}{p_0} \cos \frac{kx}{L} \tag{26}$$

$$\mathbf{V}=\frac{kp_0}{n\pi L} \frac{\sigma(q\mathbf{i}-f\mathbf{j})}{q(q^2+f^2)} Ae^{qt} \cos \frac{n\pi p}{p_0} \sin \frac{kx}{L} \tag{27}$$

$$\alpha=(\sigma/q)\omega. \tag{28}$$

Circularly symmetric solutions are identical to the above except for the replacement of cosine and sine functions by Bessel functions of order zero and one, respectively.

Figure 1 shows horizontal profiles of the above solutions for ω, Φ, and the divergent velocity component, and figure 2 illustrates the vertical variation of ω and $\mathcal{D}$, the horizontal divergence. We see that for real positive q, upward motion in the center ($A<0$) corresponds to negative perturbation geopotential and convergent cyclonic indraft in the lower levels ($p/p_0>0.5$) and to positive geopotential and anticyclonic divergent outdraft in the upper levels. The specific volume (and temperature) perturbation has its maximum in the middle levels, and is positive for $\sigma<0$. The ratio of the divergent to the rotational wind velocity can be seen, from (27), to be equal to q/f, which the wave equation shows to be a function of static stability and the scale of motion. We also note that solutions for all the dependent variables oscillate out to infinity. This will not be true for subsequent cases in which σ is allowed to vary with the sign of the vertical motion.

The dynamic stability criterion arising from wave equation (25) is the following:

$$\left(\frac{L}{p_0/n}\right)^2 \lesseqgtr -\sigma\left(\frac{k}{\pi f}\right)^2 \quad \begin{cases} \text{Unstable} \\ \text{Neutral} \\ \text{Stable} \end{cases} \tag{29}$$

Unstable solutions may exist only for $\sigma<0$ and then only if the ratio of the horizontal to the vertical scale is sufficiently small. For example, if we set in $\sigma=-3\times 10^{-3}$ m.^{2} mb.$^{-2}$ sec.$^{-2}$ as a reasonable order of magnitude (justified in a later section) we find that unstable waves may exist at latitude 20° for $L<500$ km. approximately, or roughly the size range of large tropical cyclones. If the stability criterion indicates imaginary q, then the solutions (24)–(28) represent standing inertio-gravitational waves. Traveling wave solutions are also possible, of course, and such waves will have a wave speed, in the Cartesian system, equal to $2|q|L/\pi$.

Equation (25) indicates that q approaches infinity if $L/p_0\rightarrow 0$. This obviously unreasonable result is due to the quasi-static assumption and neglect of acceleration terms in the vertical equation of motion. If these terms are included in a derivation in the x, y, z system, as was exhibited by Haque [8], and the terms in the resulting wave equation transformed to a similar form to those in (25), the latter is modified as follows:

$$q^2=\frac{-f^2-\sigma\left(\dfrac{p_0/n\pi}{L/k}\right)^2}{1+\left(\dfrac{\bar{\bar{\alpha}}}{g}\,\dfrac{p_0/n\pi}{L/k}\right)^2} \tag{30}$$

where $\bar{\bar{\alpha}}$ is a specific volume averaged through the depth of the system. Evaluation of the second term of the denominator shows it to be small for $L\gg 10$ km., i.e. (30) reduces to (25), but rapidly increasing for smaller disturbances. This corresponds roughly to the scale of motion for which nonhydrostatic terms are of impor-

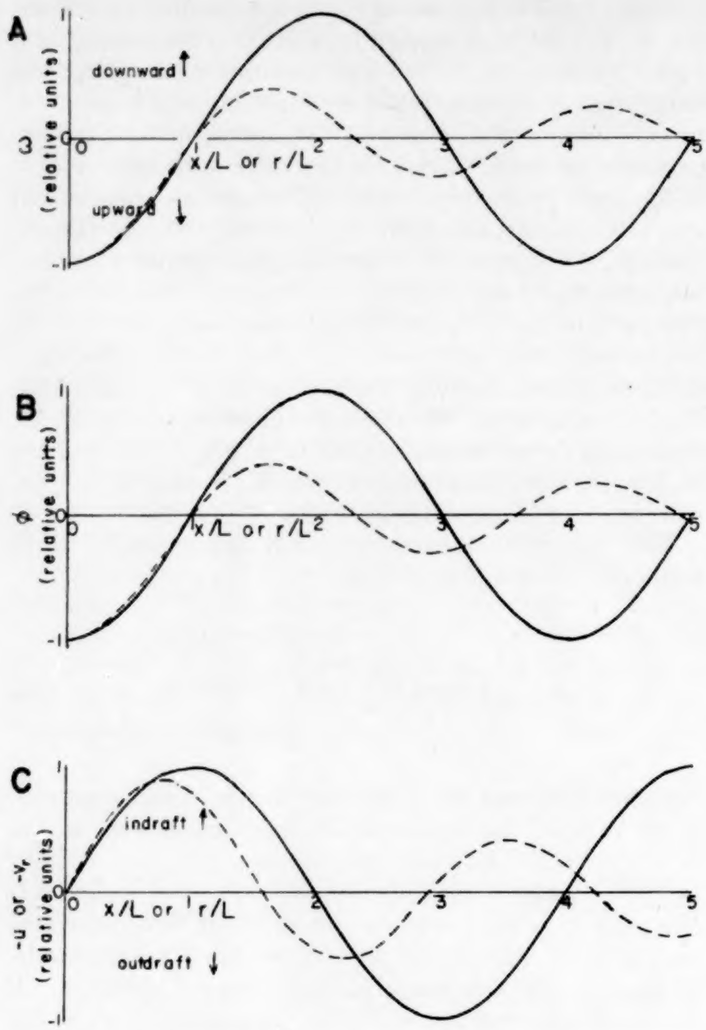

FIGURE 1.—Type I horizontal solutions, moist motions everywhere. Slab symmetry (solid), circular symmetry (dashed). (A) ω at $p=p_0/2$. (B) Φ at $p=p_0$. (C) $(-u)$ or $(-v_r)$ at $p=p_0$.

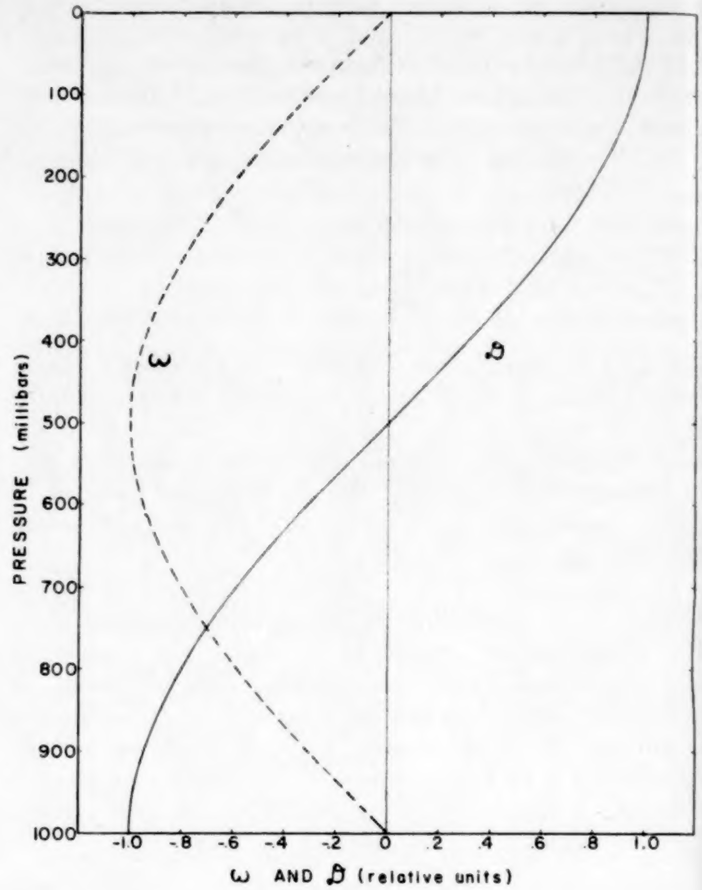

FIGURE 2.—Type I vertical solutions. $\mathcal{D}$ (solid line), ω (dashed line) scale units normalized by maximum abscissae.

tance. As $L/p\rightarrow 0$, that is, for very narrow, "tall" disturbances, (30) reduces to

$$q^2=-\left(\frac{g}{\bar{\bar{\alpha}}}\right)^2\sigma \tag{31}$$

which then represents a finite maximum growth rate and, of course, indicates that the Coriolis term is unimportant for small scales of motion. The dependence of q on horizontal scale and static stability is shown in figure 3, in which $n=1$, $p_0=1000$ mb., $\bar{\bar{\alpha}}=1.4\times 10^3$ cm.^{3} gm.$^{-1}$, $k=\pi/2$, and $f=5\times 10^{-5}$ sec.$^{-1}$

Equation (30) and figure 3 show that the maximum growth rate occurs for $L=0$. Since observations show that most rapidly growing cloud convection cells are roughly as wide as they are tall, one might expect to find the real maximum growth rate to exist for $L\approx 10$ km. This discrepancy is caused by the neglect of internal viscosity, diffusion, and entrainment effects in the present model (cf. Godske et al. [7], chapter 9).

A more important discrepancy between the stability theory and observations lies in the frequent occurrence of large-amplitude convective disturbances of horizontal dimensions much greater than those having the maximum linear growth rate. Full understanding of this bimodal tendency will doubtless require thorough consideration of nonlinear and dissipative effects, and the role of large-scale, quasi-steady-state motions in accumulating moisture at higher altitudes than normal. Linear theory can provide certain necessary conditions for further development of preexisting disturbances of a given scale and shape. It can say a little about the expected relative frequency of various disturbance scales, and also say a little about the effects of widely different scales upon each other.

5. TYPE II SOLUTIONS

We next consider the effects of the horizontal variation of static stability and, in particular, the variation caused by a discontinuous change in the polytropic exponent, as

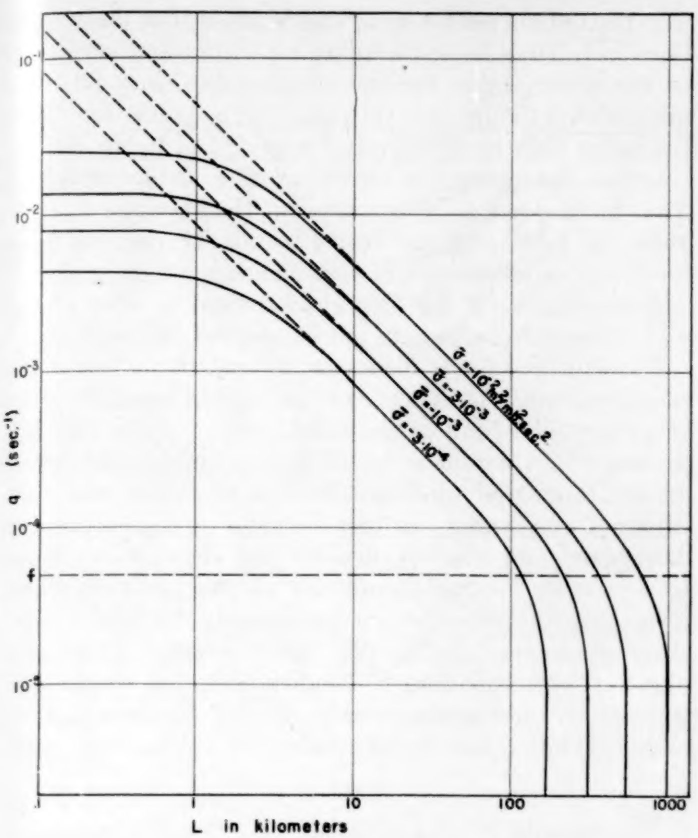

FIGURE 3.—Wave equation (25), dotted line, and (30), solid line, for various values of σ shown on the curves. $f=5\times10^{-5}$ sec.$^{-1}$, $p_0=1000$ mb. $n=1$, $k=\pi/2$.

from a moist to a dry process. We assume for simplicity that σ is a negative constant in one or more moist regions and a positive constant elsewhere. Of the various possible geometric arrangements of the moist and dry regions, the following cases have been chosen for presentation as holding particular physical interest.

Case 1: Moist (statically unstable) ascent in the center, surrounded by dry (statically stable) descent out to infinity:

(a) Slab symmetry (Cartesian coordinates).

(b) Circular symmetry (cylindrical coordinates).

Case 2: Same as case 1 except horizontally bounded by rigid walls at finite distances (slab symmetry only).

Case 3: Dry descent in the center, surrounded by moist ascent and dry descent outside to infinity (slab).

Case 4: Moist ascent in the center, surrounded by (infinitely) many alternating bands of dry descent and moist ascent, dry descent outside to infinity (slab).

CASE 1

Case 1 is the simplest possible model in which compensating dry descent is included. The principal result of the development is the appearance of a transcendental equation obtained from application of the internal boundary condition to the otherwise independent solutions for the moist and dry regions. This transcendental, which we call the compatibility condition, serves to define a dynamically effective static stability, $\bar{\sigma}$, in terms of the values of σ in the moist and dry regions and their geometric relationships. We then can replace σ by $\bar{\sigma}$ in the wave equations and stability criteria derived for the type I solution and the latter maintain their essential significance. Also in case 1 the differences between circular and slab symmetry are investigated and presented.

We consider two solutions to equations (17), (8), and (12), one valid within an inner region, $|x|$ or $r<L$, where $\sigma=\sigma_w<0$, and the second outside this region, where $\sigma=\sigma_d>0$. Thus L is now defined as the half-width or radius of the moist motions only. For each of the regions variables may be separated in (17) exactly as for type I, and solutions to equation (18) are identical with those of the former example. We will henceforth in this section set $n=1$; i.e., only one vertical mode of oscillation will be considered. Finally we define $\bar{\sigma}$ to satisfy the wave equation, that is

$$q^2+f^2=-\bar{\sigma}\left(\frac{p_0/n\pi}{L/k}\right)^2 \qquad (32)$$

Under these conditions the horizontal differential equation (19) may be solved separately for the moist and dry regions with apparently independent amplitude constants. Application of the internal boundary conditions (14), however, constrains these constants and further generates a condition of compatibility between the solutions for the adjoining regions, which is for the slab and circular symmetry case respectively.

$$\tan\,[k(\bar{\sigma}/\sigma_w)^{1/2}]=(-\sigma_w/\sigma_d)^{1/2},\ k=\pi/2 \qquad (33a)$$

$$\frac{J_1[k(\bar{\sigma}/\sigma_w)^{1/2}]K_0[k(-\bar{\sigma}/\sigma_d)^{1/2}]}{J_0[k(\bar{\sigma}/\sigma_w)^{1/2}]K_1[k(-\bar{\sigma}/\sigma_d)^{1/2}]}=\left(\frac{-\sigma_w}{\sigma_d}\right)^{1/2},\ k=2.405\ldots \qquad (33b)$$

where J_n and K_n are the nth-order Bessel functions of real and imaginary argument, respectively, which vanish at infinity (see Watson [23]).

The solutions for ω in the moist and dry regions for slab symmetry are as follows:

$$\omega_w=Ae^{qt}\sin\frac{\pi p}{p_0}\cos\frac{k(\bar{\sigma}/\sigma_w)^{1/2}x}{L},\ |x|<L \qquad (34)$$

$$\omega_d=\frac{\sigma_w}{\sigma_d}\cos\,[k(\bar{\sigma}/\sigma_w)^{1/2}]\,Ae^{qt}\sin\frac{\pi p}{p_0}$$
$$\times\exp\,[k(-\bar{\sigma}/\sigma_d)^{1/2}\,(1-|x|/L)],\ |x|>L \qquad (35)$$

Solutions for the remaining independent variables and the circularly symmetric solutions are related to those above in a similar manner with (24)-(28).

The horizontally variable part of the solutions for ω, Φ, and u or v_r (radial velocity) are shown in figure 4. In comparing these with type I we note, first, the difference in behavior for large $|x|$ or r. In this case the geopotential, vertical and horizontal velocity, etc., fall off exponentially

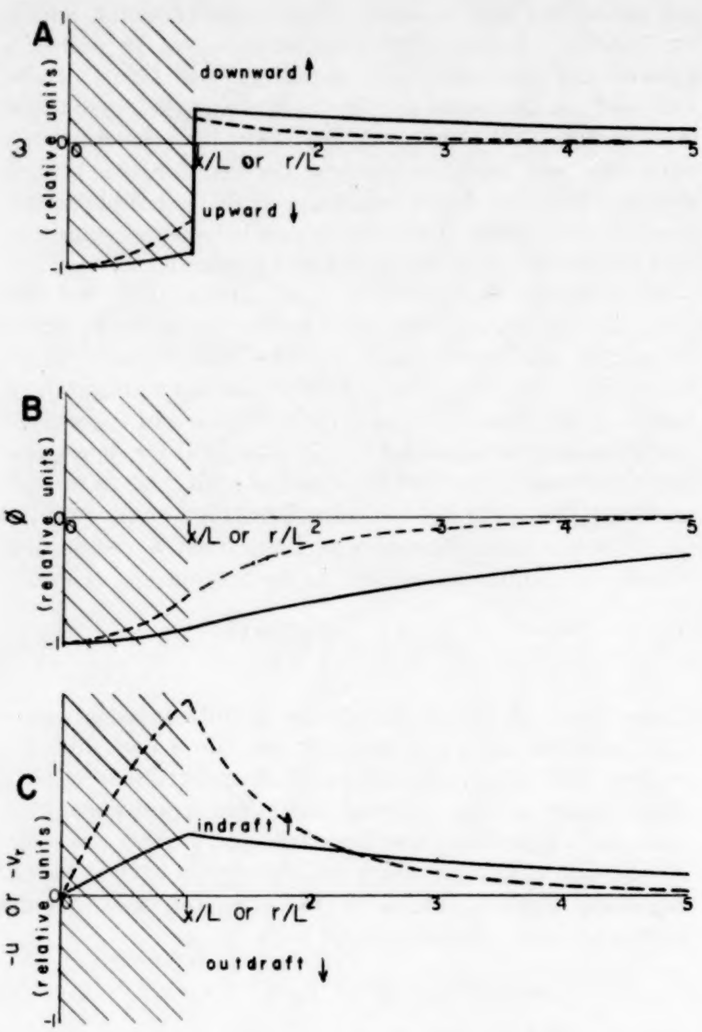

FIGURE 4.—Type II, case 1, horizontal solutions, moist region hatched. Slab symmetry (solid), circular symmetry (dashed). (A) ω at $p=p_0/2$. (B) Φ at $p=p_0$. (C) $(-u)$ or $(-v_r)$ at $p=p_0$.

in the dry region, showing the passive forced nature of the dry motions. At the same time the dry motions act somewhat as a brake upon the instability. The ratio of the effective stability to the moist stability, $\bar{\sigma}/\sigma_w$, has been computed for both the slab and circular solutions for various values of σ_w/σ_d, and is shown in table 2.

We note that the reduction is much greater for slab than for circular symmetry, thus favoring development of the latter. The reason for this behavior seems to lie in the more compact nature of the circular disturbance.

TABLE 2.—*The ratio of effective stability to moist stability for various values of the ratio of moist to dry stability*

$-\sigma_w/\sigma_d$	0.0	0.1	0.3	0.5	1.0	10.0	∞
$\bar{\sigma}/\sigma_w$ Circular	0.0	0.211	0.299	0.357	0.451	0.760	1.000
$\bar{\sigma}/\sigma_w$ Slab	0.0	0.037	0.101	0.153	0.250	0.624	1.000

The plotted curves for Φ, ω, and **V** show that these functions have their largest amplitudes within and very close to the moist region for the circular case, but exhibit a much slower damping in the case of slab symmetry. Thus the latter may be effectively "larger" and hence less active than the former, for a given width of the moist region. Thus bands seem to be less efficient than circular disturbances for release of convective instability and the large frequency of occurrence of such bands must be explained as a consequence of the vertical wind shear or other effects, e.g., turbulent dissipation, not considered in this study.

The solutions for **V** show that the maximum radial and tangential winds both occur at the internal boundary, that is, at the outer limit of the moist region. In section 9 it is shown that nonlinear terms have a considerable effect on the tangential wind distribution at rather small disturbance amplitudes. It may be noted that ω, horizontal divergence, and relative vorticity (not shown) are discontinuous at the internal boundaries. In the real atmosphere these discontinuities would presumably be replaced by sharp gradients. In the dry region relative vorticity is negative, corresponding to conditions in the outskirts of tropical cyclones as observed by several Japanese meteorologists (Ootani and Hatakeyama [16]; Syōno et al. [22]).

CASE 2

The boundary conditions for case 2 are identical to those obtainable under the assumption that another disturbance of identical scale and amplitude adjoins on either side of the one under consideration. Thus we may investigate the behavior of a convective band and the constraints imposed upon it by the existence of neighboring bands. An interesting result is the appearance of a limitation on the ratio of horizontal extent of the moist and dry regions for existance of unstable solutions; that is, a limiting proximity of adjoining bands. The external boundary condition here consists of vanishing of the wind component normal to the wall. After applying this condition to the elementary solutions of (17), it is found that ω_w is unchanged, but ω_d is replaced, for the slab symmetric case, by an expression involving hyperbolic cosines. The fields of ω, Φ, and u are illustrated, for this case, in figure 5. The compatibility condition is altered to the following form:

$$\frac{\tan\,[k(\bar{\sigma}/\sigma_w)^{1/2}]}{\tanh\,[k(-\bar{\sigma}/\sigma_d)^{1/2}(x_1-L)]}=\left(-\frac{\sigma_w}{\sigma_d}\right)^{1/2} \tag{36}$$

where $\pm x_1$ is the abscissa of the external boundary, and thus x_1-L is the half-width of the dry region.

Examination of (36) shows that the horizontal constraint reduces the effective instability, and $\bar{\sigma}$ vanishes for $(x_1-L)/L=-\sigma_d/\sigma_w$. This is the minimum ratio of the separation of convective bands to their width, i.e. the clear-cloud ratio, for which the bands may amplify. Depending on the vertical dimension of the disturbances, table 1 indicates that this ratio may vary from about one to three in the mean tropical troposphere. This revision of the stability

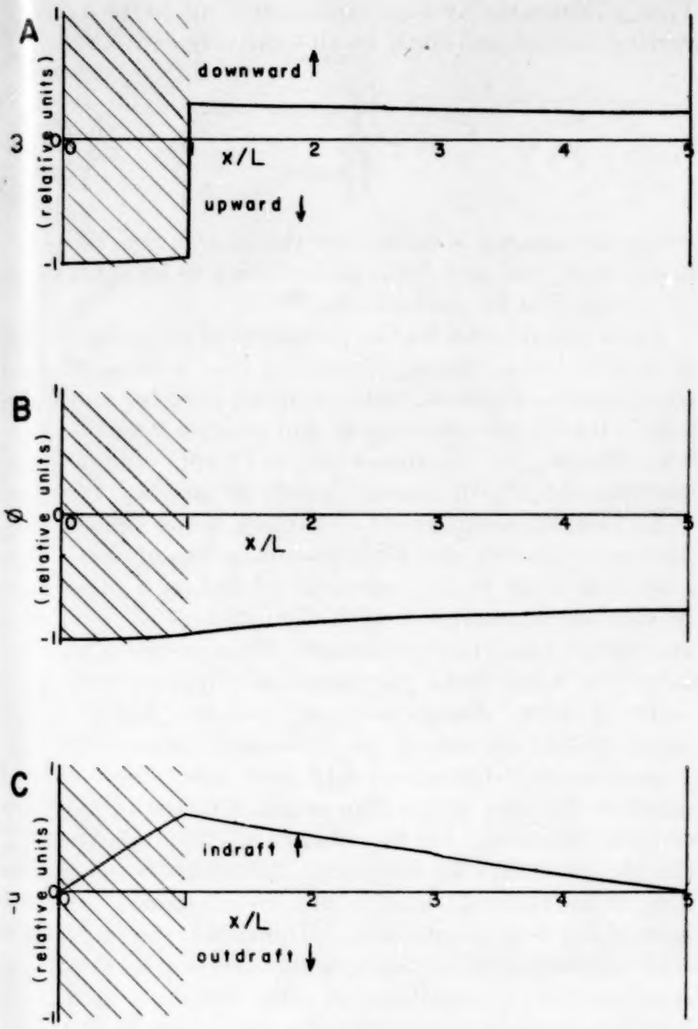

FIGURE 5.—Type II, case 2, horizontal solutions, moist region hatched. (A) ω at $p=p_0/2$. (B) Φ at $p=p_0$. (C) $(-u)$ at $p=p_0$.

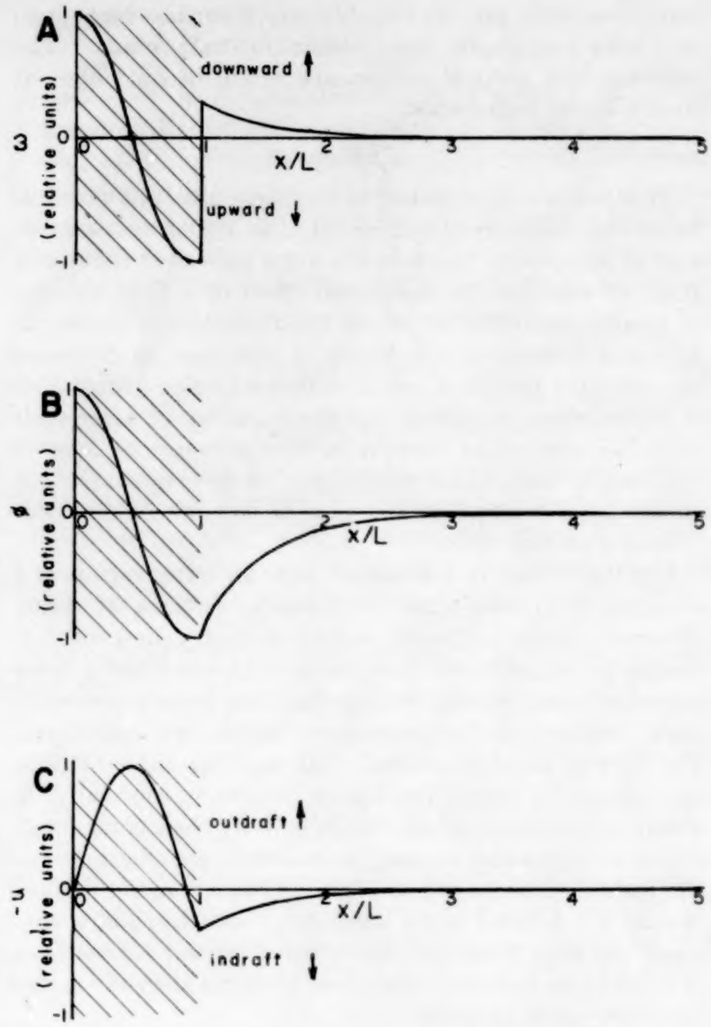

FIGURE 6.—Type II, case 3, horizontal solutions, moist region hatched. (A) ω at $p=p_0/2$. (B) Φ at $p=p_0$. (C) $(-u)$ at $p=p_0$.

criterion bears a close relation to the conclusions of the "slice" method of forecasting convection, first introduced by J. Bjerknes [2].

CASE 3

Taking the radius of the "eye" equal to a, where $a<L$, we specify a stability distribution as follows:

$$\left.\begin{array}{ll}\sigma=\sigma_d, & |x|<a\\ \sigma=\sigma_w, & a<|x|<L\\ \sigma=\sigma_d, & |x|>L.\end{array}\right\} \qquad (37)$$

The horizontal solution for ω, with slab symmetry, is proportional to the hyperbolic cosine in the eye, sinusoidal in the moist region, and as before, a decreasing exponential outside. The horizontal profiles of ω, Φ, and u are exhibited in figure 6; circularly symmetric solutions are similar in appearance. The compatibility condition becomes

$$\tan\left[\frac{k(\bar{\sigma}/\sigma_w)^{1/2}(L-a)}{L}\right] =\left(\frac{-\sigma_w}{\sigma_d}\right)^{1/2}\frac{1+\tanh\,[k(-\bar{\sigma}/\sigma_d)^{1/2}a/L]}{1+(\sigma_w/\sigma_d)\tanh\,[k(-\bar{\sigma}/\sigma_d)^{1/2}a/L]}. \qquad (38)$$

By comparison of (38) with (33), it can be seen that $\bar{\sigma}$ is greater for this case, and the "eye" tends to increase the growth rate. The amount of this increase however, is insignificant. For $\sigma_w=-0.3\times10^{-3}$ and circular symmetry, an eye with a radius of 0.1 L ($\frac{1}{10}$ that of the moist region) increases effective static instability by less than 2 percent, thus changing the wave equation only very slightly. Although the eye plays an indispensable part in maintenance of a tropical cyclone, as first shown by Haurwitz [9], it evidently does so by means of nonlinear terms not considered in this study.

The vertical motion distribution in the eye case, as shown in figure 6, exhibits a downdraft region in the eye,

associated with an indetectably slight surface high pressure area and slight anticyclonic outdraft winds. The vorticity and vertical motion are again discontinuous at both internal boundaries.

CASE 4

This case was also picked to represent a certain physical feature of the tropical cyclone; that is, the observed existence of convective bands in the outer regions of the storm. Here we consider the integrated effect of a large number of smaller disturbances of the type considered in case 2. A rather interesting conclusion of this case, in combination with the results of case 2, is that a forcing disturbance is a necessary condition for development of large-scale unstable convective motion in the presence of smaller scale convection. This conclusion is a consequence of the effects upon a large-scale system of the dry descent surrounding smaller cells.

For this model it is assumed that an inner region of a developing cyclone-scale disturbance consists of many alternate bands of moist ascent and dry descent. It should be remembered that the growth exponent q is assumed constant throughout, so that only the quasi-steady-state features of the meso-scale bands are considered. The shorter lived cloud-scale cells may be thought of as generating the proper conditions (moisture, especially) to assure maintenance of the bands and, by their compensating downdrafts and drying, to maintain spacing between the bands, according to the spacing requirements derived in case 2. A band is, for simplicity, considered at a constant distance from the disturbance center, rather than parallel to the low-level wind flow, as seems to be the actual case in tropical cyclones.

Methods used for finding solutions for the previous cases become tedious when a large number of narrow bands is assumed. Instead it is desirable to define some sort of averaged stability value appropriate to an area containing an infinite number of alternating moist and dry bands, which we do in the following manner. Consider two infinitesimal bands, one moist with stability $\sigma_w<0$ and the other dry with stability $\sigma_d>0$, and let the ratio of the width of the moist band to that of the total width of both be U. Since the bands are considered infinitesimal relative to the large-scale disturbance, we may consider that in each of the moist and dry bands Φ is approximately horizontally constant, and by application of (14) Φ is therefore approximately constant over both bands. Further, $\partial^2\Phi/\partial p\partial t$ is also approximately constant and, by application of (2) and (4), $\sigma_w\omega_w\approx\sigma_d\omega_d$, where ω_w and ω_d are the (approximately horizontally constant) vertical velocities in the moist and dry bands, respectively. If we define the average value of ω (across both bands) to be $\bar{\omega}=U\omega_w+(1-U)\omega_d$, then $\tilde{\sigma}\bar{\omega}=\sigma_w\omega_w=\sigma_d\omega_d$ if

$$\frac{1}{\tilde{\sigma}}=\frac{U}{\sigma_w}+\frac{1-U}{\sigma_d} \tag{39}$$

Thus $\tilde{\sigma}$ relates the average expansion of air to the average vertical motion and could be alternatively defined as

$$\tilde{\sigma}=\frac{\iint\sigma\omega dxdy}{\iint\omega dxdy} \tag{40}$$

where the integral is taken over the banded region. If U is constant, (39) and (40) can be shown to be equivalent. We define $\tilde{\sigma}$ to be the band stability.

From (40) one can see the possibility of an infinite value of $\tilde{\sigma}$, if $U=-\sigma_w/(\sigma_d-\sigma_w)$, implying that heat is released from vertical motions, but the mean vertical motion is zero. In this case divergence and relative vorticity vanish. Hughes [11] has shown this to be approximately the condition in the outer rain bands of tropical cyclones.

An even more significant conclusion comes from a comparison of relation (39) with the conclusions of case 2. In case 2 we look at the convective band as a meso-scale phenomenon, associated with disturbances of small size and rather rapid time variations, while in case 4 we consider the band from the large-scale quasi-steady-state point of view, disregarding all transient features. In equation (36) and subsequent discussion it was shown that a small-scale disturbance could grow only if the ratio of moist to dry area is *less* than or equal to the ratio of dry to moist stability. On the other hand, (39) indicates that the band stability for large-scale disturbances is negative only if the ratio of moist to dry area is *greater* than the ratio of dry to moist stability. This means that a cyclone-scale convective disturbance cannot develop as simply an amalgamation of smaller-scale cells, but must include at least a meso-scale central core of moist ascent, presumably generated by a disturbance whose energy is derived from other than convective instabilities.

Having postulated the existence of such a core we now assume three distinct regions with different values of stability; i.e.,

$$\left.\begin{aligned}\sigma&=\sigma_w<0, & |x|&<b\\ \sigma&=\sigma_b\rightarrow-\infty, & b<|x|&<2L-b\\ \sigma&=\sigma_d>0, & |x|&>2L-b\end{aligned}\right\} \tag{41}$$

where $2(L-b)$ is the width of the banded region. The solutions for Φ in the inner and outer regions are similar to those of case 1, while that for the banded region shows a linear variation with x (logarithmic with r for circular symmetry). These solutions are exhibited in figure 7. The compatibility condition is found to be the following:

$$\tan\,[k(\bar{\sigma}/\sigma_w)^{1/2}b/L]=[(-\sigma_d/\sigma_w)^{1/2}-2k(\bar{\sigma}/\sigma_w)^{1/2}(L-b)/L]^{-1} \tag{42}$$

which shows that the banded region has a dynamic effect midway between that of an all-dry and an all-moist region.

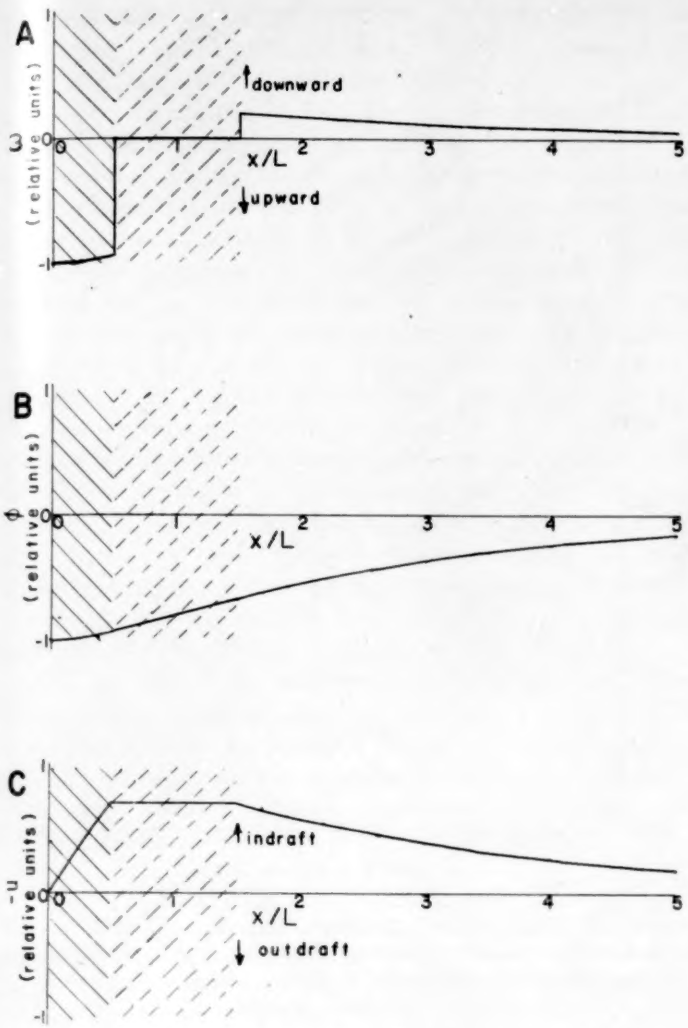

FIGURE 7.—Type II, case 4, horizontal solutions, moist region hatched solidly, banded region hatched lightly. (A) ω at $p=p_0/2$. (B) Φ at $p=p_0$. (C) $(-u)$ at $p=p_0$.

6. TYPE III SOLUTIONS

Considering σ to be a function of pressure, we again separate variables in (17). The resulting reduced equations may be formally written in the same form as (18) and (23), and the wave equation (25) holds for an effective stability $\bar{\sigma}$, provided that σ, $\bar{\sigma}$, and K are related by the expression

$$K=(\sigma/\bar{\sigma})^{1/2}n\pi \tag{43}$$

Thus, $\bar{\sigma}$, which may be a function of n, can be found from solution of (18) with boundary conditions. Again we specify $n=1$ for purposes of this study. In this section two cases are exhibited.

Case 1: Constant negative stability in the troposphere, constant temperature in the stratosphere.

Case 2: Stability values equal to σ_w in table 1 for pressures above 100 mb., constant temperature for pressures below 100 mb.

CASE 1

Here we investigate the effects of a sharp tropopause discontinuity in static stability. It is shown that the stratosphere acts effectively as a lid to the disturbance and can be considered as equivalent to applying a solid surface boundary condition at a level slightly above the tropopause.

We prescribe σ for the lower and upper layers, respectively, by the following expressions:

$$\sigma=\sigma_T<0 \text{ for } p>p_T \tag{44a}$$

$$\sigma=\sigma_S=R^2\overline{T}_S/c_p p^2 \text{ for } p<p_T \tag{44b}$$

where σ_T is a negative constant and equation (44b) is obtained from (7) with $\overline{T}_S$ the stratosphere temperature. Solutions to (18), with K evaluated from (43), (44a), and (44b), satisfying the external boundary conditions (8) and (12) may be written as follows:

$$P=A_T \sin[\pi(\sigma_T/\bar{\sigma})^{1/2}(p_0-p)/p_0],\ p>p_T \tag{45a}$$

$$P=A_S(p/p_0)^{1/2+N},\ p<p_T \tag{45b}$$

where

$$N^2=\frac{1}{4}-\frac{R^2\overline{T}_S}{c_p p_0^2\bar{\sigma}}.$$

Internal boundary conditions (15) lead to a relation between the amplitude coefficients A_S and A_T and to a compatibility condition which can be solved to yield $\bar{\sigma}$. This may be written

$$\tan[\pi(\sigma_T/\bar{\sigma})^{1/2}(p_0-p_T)/p_0]=-\left(N+\frac{1}{2}\right)[\pi(\sigma_T/\bar{\sigma})^{1/2}p_T/p_0]. \tag{46}$$

Solution of (46) shows that $\bar{\sigma}/\sigma_w<1$. We now show that reduction of instability by the presence of the stratosphere is identical to the effect of a rigid boundary at $p=p_H$, where $p_H<p_T$. We set $\sigma=\sigma_T$ for all $p>p_H$, and define p_H by the relation

$$(p_0-p_H)/p_0=(\bar{\sigma}/\sigma_T)^{1/2}. \tag{47}$$

Substitution of (47) into (45a) shows that P, and therefore ω, vanishes at $p=p_H$. Values of p_H and $\bar{\sigma}/\sigma_T$ computed from (46) and (47) for various values of p_T are given in table 3.

TABLE 3.—*The equivalent rigid tropopause level, p_H, and the effective static stability, $\bar{\sigma}$, for various values of the tropopause pressure, p_T*

p_T (mb.)	$\bar{\sigma}/\sigma_T$	p_H (mb.)
100	0.914	86
150	.870	130
200	.826	174
250	.781	219

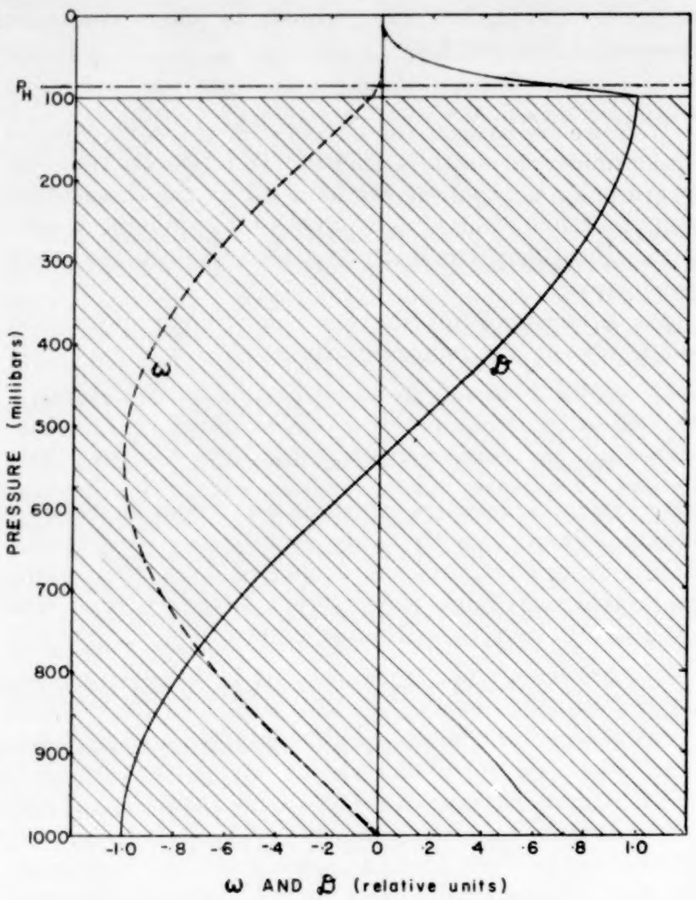

FIGURE 8.—Type III, case I, vertical solutions $\mathcal{D}$ (solid line), ω (dashed line), scale units normalized by maximum abscissae. Dash-dotted line represents equivalent rigid tropopause. Hatched area is statically unstable.

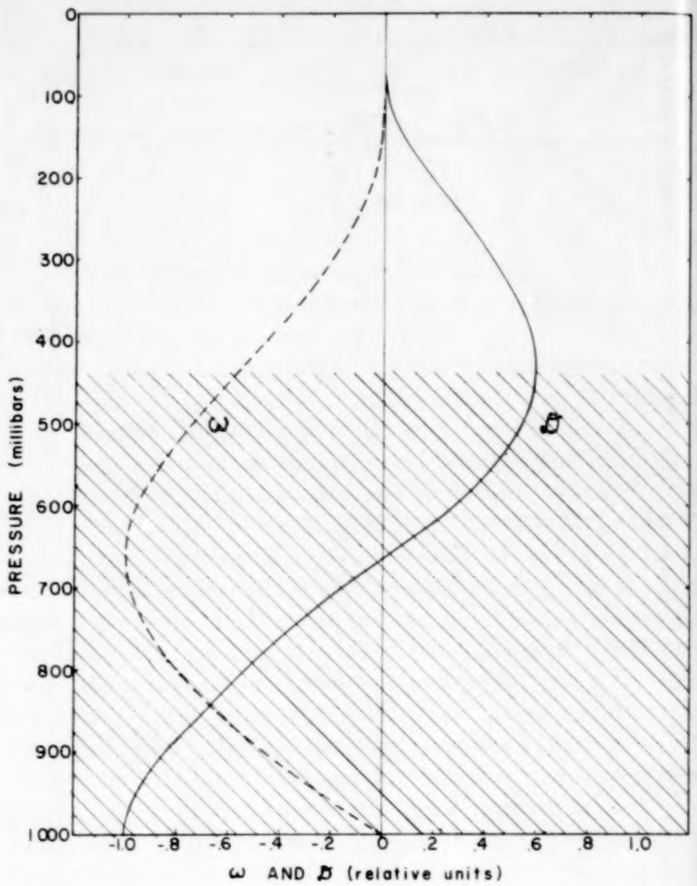

FIGURE 9.—Type III, case 2, vertical solutions. $\mathcal{D}$ (solid line), ω (dashed line), scale units normalized by maximum abscissae. Hatched area is conditionally unstable.

Solutions of case 1 for ω and $\mathcal{D}$ are presented in figure 8 for $p_T=100$ mb., $\sigma_T=-3\times10^{-3}$m.^{2}mb.$^{-2}$sec.$^{-2}$, and $\overline{T}_S=200°$ K. The curves further illustrate the extremely rapid decrease of disturbance amplitude above the tropopause.

CASE 2

Here the distribution of stability with height is relatively smooth. The results of the numerical integration of (18) for this case show, however, that again the principal effect of an upper stable layer is to diminish the effective depth of a disturbance and reduce its growth rate correspondingly.

The solution for this case was found by numerical integration of (18) using (43), and with $\sigma=\sigma_w$, evaluated from table 1 for $p>100$ mb., and σ taken from (44b) for $p<100$ mb., where $\overline{T}_S=200°$ K. The Gill [6] formulation of the Runge-Kutta integration scheme, as programmed for the IBM 704, was utilized in forward integration from one boundary to the other. An initial guess of $\overline{\sigma}$ was made, and this was improved by means of Newton-Raphson iteration methods until both boundary conditions (8) and (12) were satisfied to sufficient accuracy. The method was checked by comparison of results for cases with known analytic solutions, such as case 1 of this section.

Figure 9 shows the solutions obtained for ω and $\mathcal{D}$. The unstable region is shaded, and above this region the disturbance amplitude rapidly decreases, becoming imperceptible in the stratosphere. The value of $\overline{\sigma}$ found for this solution is -2.732×10^{-3} m.^{2} mb.$^{-2}$ sec.$^{-2}$. This result provides justification for the value of -3×10^{-3} used in evaluation of the stability criterion.

In comparing the sinusoidal vertical solutions of type I, equations (24)–(28) and figure 2, with those of this section, we note that the sign of the geopotential disturbance reverses from low to high levels in both cases. This is generally true for any solution of the linear set (1)–(4) in which there is a reversal of the sign of divergence with height, since Φ is proportional to $\mathcal{D}$. This proportionality

does not seem to accord with the true situation in well-developed tropical cyclones, which exhibit cyclonic rotation and negative disturbance geopotentials to great heights in their inner regions, and at the same time large negative values of relative vorticity and divergence.

In order to explain the disparity between the model and observations, attention is directed to the nonlinear terms of the motion equations. We show in a later section that those advective terms do seem to be responsible for extending the cyclonic wind field to higher levels as the disturbance amplitude becomes significant. In the very early stages the circulation reversal might be observed, but even then it could be masked if the disturbance developed within a preexisting circulation.

In order to further investigate this problem, one could set up perturbation equations on a basic nondivergent vortex. These equations become quite complicated when both horizontal and vertical shears are involved, and analytic solutions are out of the question for any physically reasonable cases. Rather than solve the perturbation equations by numerical methods, it would seem more profitable to solve the nonlinear equations directly, as an initial value problem. Berkofsky [1] has developed a numerical scheme for doing this. A deficiency of Berkofsky's model is that it excludes gravitational waves by means of a balance equation, and thereby eliminates the type of linear motions discussed in this paper.

7. SURFACE FRICTIONAL EFFECTS

If one assumes that a frictionally-forced updraft can be adequately expressed as a boundary condition of the form of (13), then this boundary condition may be used, in place of (12), to determine coefficients of the elementary solutions of (18). The resulting transcendental may be used, as with the type III solutions, to define an effective static stability, $\bar{\sigma}$, which satisfies the wave equation. The definition may be written as:

$$\frac{\tan\left[(\sigma/\bar{\sigma})^{1/2}\pi p_F/p_0\right]}{(\sigma/\bar{\sigma})^{1/2}\pi}=-\frac{q^2+f^2}{qf}\,B\,\frac{p_0-p_F}{p_0} \tag{48}$$

where we assume that $0<B<1$ for $q<f$ and $-1<B<0$ for $q>f$, and $p_F\approx 900$ mb.$=0.9p_0$. For large disturbances, where $q\ll f$, the argument of the tangent approaches $\pi/2$. Therefore $(\bar{\sigma}/\sigma)^{1/2}\approx 2$ and the largest unstable disturbance diameter is nearly doubled. On the other hand small disturbances with $q\gg f$ lead to values of $(\bar{\sigma}/\sigma)^{1/2}<1$.

8. ENERGY RELATIONS

It is of interest to consider the energy transformations and transports in our linearized system. The kinetic energy equation, obtained by dot multiplication of (1) by $\mathbf{V}$, may be written as follows:

$$\frac{\partial \mathscr{K}}{\partial t}=-\nabla\cdot(\mathbf{V}\Phi)-\frac{\partial}{\partial p}(\omega\Phi)-\alpha\omega \tag{49}$$

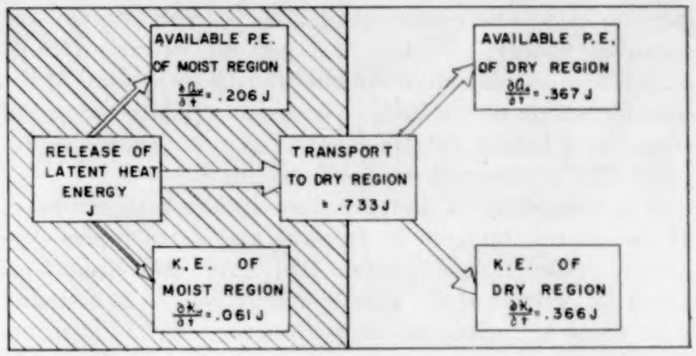

FIGURE 10.—Partition of energy released by latent heat of condensation. Hatched area represents the moist unstable region.

where $\mathscr{K}=\mathbf{V}\cdot\mathbf{V}/2$. If (49) is integrated over all space, given external lateral boundary conditions as prescribed in section 3, and ω vanishing at the upper and lower boundaries, the first two terms on the right vanish. After multiplying (4) by α/σ_d, where σ_d is the static stability for dry processes, we obtain an equation for available potential energy, similar to that defined by Lorenz [13].

$$\frac{\partial A}{\partial t}=\frac{\sigma}{\sigma_d}\,\alpha\omega \tag{50}$$

where $A=\alpha^2/2\sigma_d$.

The integrated sum of (49) and (50) vanishes for dry processes, so that $(-\alpha\omega)$ is clearly the transformation from available potential to kinetic energy for the dry process. For moist motions, where $\sigma=\sigma_w$, the term $(\sigma_d-\sigma_w)\alpha\omega/\sigma_w$ is evidently the transformation of latent heat to available potential energy and is positive when σ_w and ω are negative and α positive.

In the type II and III solutions of this study the energy relations are complicated somewhat by transports across the internal boundaries. The complete budget has been evaluated for type II, case 1, and shows several interesting features. If we assume $(\bar{\sigma}/\sigma_w)^{1/2}=0.3$, from table 2, and express all quantities as multiples of J, the total released latent heat energy, the following results are obtained.

$$\left.\begin{aligned}\frac{\partial \bar{A}_d}{\partial t}&=0.367J; &\quad \frac{\partial \bar{A}_w}{\partial t}&=0.206J\\ \frac{\partial \bar{\mathscr{K}}_d}{\partial t}&=0.366J; &\quad \frac{\partial \bar{\mathscr{K}}_w}{\partial t}&=0.061J\end{aligned}\right\} \tag{51}$$

where $J=0.585\,(-\sigma_w/q)\,A^2e^{2qt}$ and $\bar{A}_d=\dfrac{1}{Lp_0}\displaystyle\int_0^L\int_0^{p_0}A_d\,dp\,dx$,

with other quantities similarly defined. Figure 10 shows the relationships of these various energy terms. We see that of the total energy released by latent heat in the moist region 26.7 percent remains within the moist region, 6.1

percent as kinetic energy, and 20.6 percent as available potential energy. Of the 73.3 percent which is transported into the dry environment (that is, nearly all of the transformation term), half is released as available potential energy and half as kinetic energy. Kinetic energy represents 42.7 percent of the total production.

It is interesting to compare these results with estimates of the energy budgets in tropical and extratropical cyclones. Palmén and Jordan [18] have estimated that about 30 percent of the kinetic energy release in a steady state tropical cyclone occurs within the inner 2° latitude, where most of the latent heat energy is released, the remaining 70 percent being released mainly in the 2°–6° ring. In our model the corresponding percentages are about 16 percent and 84 percent. Palmén and Jordan find, however, that the total kinetic energy released is only about 2½ percent of the total latent heat energy released, as compared to our 42.7 percent. Palmén [17] in his analysis of hurricane Hazel, found that the kinetic energy released during the period of transformation from a tropical to an extratropical cyclone was about 12.5 percent of the latent heat energy released, but he was unable to estimate the transformation of available potential to kinetic energy during this time.

It seems, therefore, that the mechanical efficiency of our model is considerably too great, as compared with real large-scale systems. This is due both to the neglect of dissipative terms in this development and to the considerable changes in dynamics as the real disturbance develops and loses both its static instability and its vertical symmetry, by means of vertical and horizontal advection.

9. NONLINEAR EFFECTS

It is recognized that the atmospheric phenomena dealt with in this study frequently attain an amplitude at which the nonlinear terms of the meteorological equations are substantially larger than some of the linear terms. This is certainly sufficient cause for an examination of the foregoing results to determine in what way they might be altered by inclusion of these nonlinear terms in the basic differential equations. One method of approximating the nonlinear effects is to substitute the linear solutions into the nonlinear terms of the complete equations and thereby obtain a second-order approximation to the true nonlinear solutions. This might be considered as the beginning of an iterative process, in which each solution generates the terms of a subsequent higher order equation. The existence and convergence of such solutions has been demonstrated by W. Malkus and Veronis [15] as applied to a Bénard convection cell problem. The process is tedious when carried out to higher orders. In fact the first iterative step for our system results in an inhomogeneous differential equation, probably only numerically solvable. We are able, however, to obtain information as to the relative orders of magnitude and general effects of the nonlinear terms.

If we regard convective disturbances as eddies within a larger-scale environment, the advective terms of the thermodynamic equation represent the eddy transport of heat. Thus from the linear solutions we may to some degree approximate the convective heat transport of the linear systems.

We define $\mathbf{V}'$, Φ', ω', and α' to be the second-order variables appearing when our linear solutions are substituted into the nonlinear terms of the motion and heat equations. Equations for these variables may be written as follows:

$$\frac{\partial \mathbf{V}'}{\partial t}+f\,\mathbf{k}\times\mathbf{V}'+\nabla\Phi'=-\mathbf{V}\cdot\nabla\mathbf{V}-\omega\frac{\partial \mathbf{V}}{\partial p} \tag{52}$$

$$\frac{\partial \Phi'}{\partial p}+\alpha'=0 \tag{53}$$

$$\nabla\cdot\mathbf{V}'+\frac{\partial \omega'}{\partial p}=0 \tag{54}$$

$$\frac{\partial \alpha'}{\partial t}-\sigma\omega'=-\mathbf{V}\cdot\nabla\alpha-\omega\left(\frac{\partial \alpha}{\partial p}+\frac{\alpha}{\kappa p}\right). \tag{55}$$

If solutions of (5) and any of the boundary conditions used in this study are substituted for the variables on the right side and the system reduced to an equation in ω', it may be shown that the inhomogeneous (nonlinear) terms are eliminated except for the last one in (55), and (52)–(55) reduce to

$$\left(\frac{\partial^2}{\partial t^2}+f^2\right)\frac{\partial^2\omega'}{\partial p^2}+\nabla^2(\sigma\omega')=\nabla^2\left(\frac{\omega\alpha}{\kappa p}\right). \tag{56}$$

A particular solution of (56) may be formally written as follows, where p' and p'' are dummy variables.

$$\omega'=\int_0^p\int_0^{p'}\cos\left[\left(\frac{q^2+f^2}{4q^2+f^2}\right)^{1/2}\frac{2\pi}{p_0}(p-2p'+p'')\right]\frac{\nabla^2(\omega\alpha/\kappa p)}{4q^2+f^2}\,dp''dp'. \tag{57}$$

In order to show the general nature of the solutions of (52)–(55), we consider a somewhat simpler case. If the atmosphere were incompressible, the last term on the right sides of (55) and (56) would vanish. This assumption alters the static stability parameter, σ, in that κ is assumed infinite. Other than this change in interpretation the nature of the perturbation equations and their solutions is entirely unchanged. In this case the particular solution for (57) is

$$\omega'=0. \tag{58}$$

This is not trivial, since the remaining terms on the right of (52) and (55) do not vanish. Φ', $\mathbf{V}'$, and α' are found to be the following:

$$\Phi'=\frac{\sigma}{4q^2}\left\{\left[\omega^2+\frac{\sigma}{\bar{\sigma}}\left(\frac{L}{k}\nabla\omega\right)^2\right]-\frac{2q^2-f^2}{q^2+f^2}\left[\omega^2+\left(\frac{p_0}{\pi}\frac{\partial\omega}{\partial p}\right)^2\right]\right\} \tag{59}$$

$$\mathbf{V}'=\frac{\sigma f}{4q^2(q^2+f^2)}\mathbf{k}\times\nabla\left[\omega^2+\left(\frac{p_0}{\pi}\frac{\partial\omega}{\partial p}\right)^2\right] \tag{60}$$

$$\alpha'=-\frac{\sigma}{4q^2}\frac{\partial}{\partial p}\left[\omega^2+\frac{\sigma}{\bar{\sigma}}\left(\frac{L}{k}\nabla\omega\right)^2\right]. \tag{61}$$

For the perturbation cases exhibited previously α' is a function of pressure only, the tangential velocity is a function only of the horizontal coordinate, and Φ' is a sum of the integrals of these one-dimensional functions. In figure 11 are shown horizontal profiles of v' and the horizontally variable part of Φ' and vertical profiles of α_w' and the vertically variable part of Φ_w', where ω_w and ω_d are obtained from the perturbation solutions of type II, case 1 with slab symmetry. The vertically variable parts of Φ_d' and α_d' vanish identically.

We are now able to verify the statements made in previous sections about the probable effects of nonlinear terms. From (59) and figure 11 one sees that the tangential wind field is changed by a term which is cyclonic at all levels within the moist region ($\sigma_w<0$), the vorticity of which has a positive maximum at the center. In the dry region there is a corresponding anticyclonic wind, but of a much smaller magnitude, proportional to $(-\sigma_w/\sigma_d)^3$ times that of the moist region. These terms evidently tend to bring the perturbation disturbance into closer agreement with tropical cyclone wind profiles.

The α' field tends principally to lift the level of the maximum heating, thus destabilizing the upper levels and allowing the developing cyclone to extend to much greater heights than the 5-km. depth of normal conditional instability in the tropical troposphere. The Φ' field is composed of two parts. The vertically variable component is the hydrostatic integral of α' and leads to decreased geopotential at intermediate pressure levels, consistent with the increasing depth of the cyclonic portion of the disturbance. The horizontally variable component of Φ' has its maximum amplitude at the center, with the sign in the moist region the same as the sign of $2q^2-f^2$. Thus if the linear disturbance is small and rapidly growing, i.e., $2q^2>f^2$, this term represents a filling tendency. If $0<2q^2<f^2$, however, both the linear and nonlinear terms provide low-level deepening at the center. The latter inequality then appears to specify a rather narrow size range within which disturbances may continue to grow to significant amplitudes, and thus represents a second-order stability criterion. It is not clear whether or how an initial disturbance might alter its size or shape to adjust to this criterion, nor is it certain how the compressibility term in (56) might change matters, but the effect may have an important bearing on the observed bimodal distribution of convective disturbances.

We now make quantitative estimates as to orders of magnitude of the nonlinear terms. If $\sigma_w=-3\times10^{-3}$m.^{2}mb.$^{-2}$ sec.$^{-2}$, and $f=5\times10^{-5}$ sec.$^{-1}$, by comparison of (59)–(61) with (26)–(28) it may be shown that α'/α and v'/v are

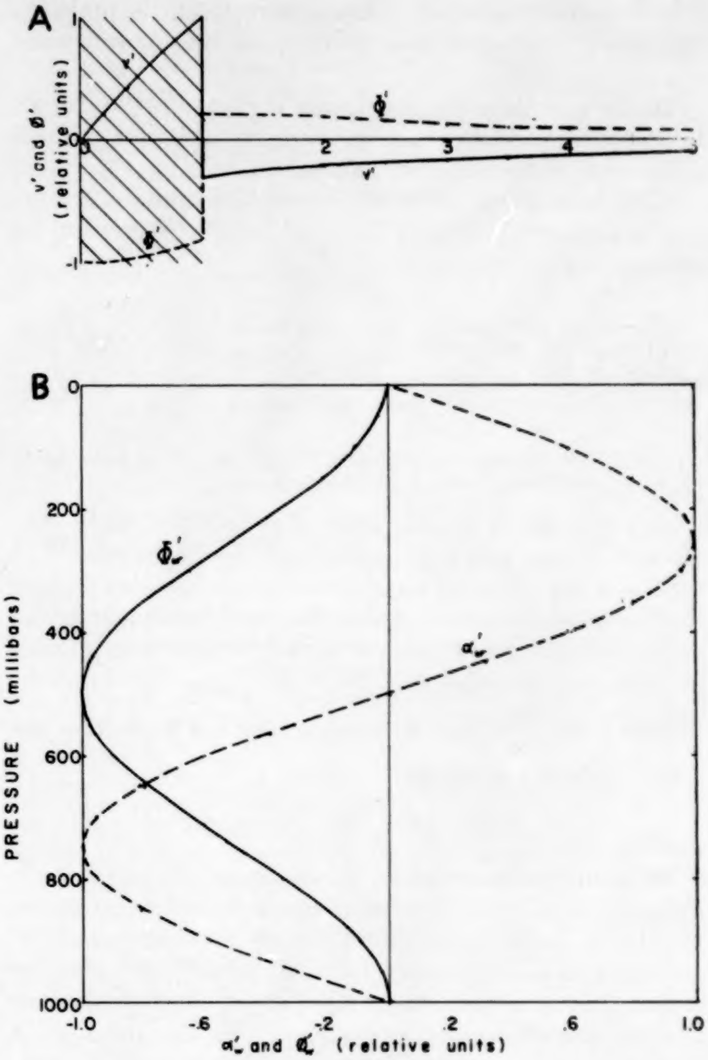

FIGURE 11.—Second-order components of nonlinear solutions for type II, case 1. (A) Horizontal profiles of v' (solid) and Φ' (dashed). Moist region hatched. Scale units normalized by maximum ordinates. (B) Vertical profiles of Φ'_w (solid) and α'_w (hatched). Scale units normalized by maximum abscissae.

approximately unity for $|\Phi|=300$ m.^{2} sec.$^{-2}$, or a surface pressure amplitude of about 4 mb. The first term of Φ' is of the order of $|\Phi|$ when $|\Phi|=600$ m.^{2} sec.$^{-2}$, a pressure amplitude of 8 mb. The second term of Φ' depends on its coefficient which may vary from -2 to $+1$. If $q=f/2$ this term is of the order of $|\Phi|$ when $|\Phi|=1500$ m.^{2} sec.$^{-2}$, a surface pressure amplitude of 20 mb. Thus the second-order stability criterion discussed above only becomes effective when the amplitude is substantial. At this stage the other nonlinear terms may have distorted the dynamics of the system so much that it is no longer applicable. In any case it is clear that the study of tropical cyclones by means of linear theory must be limited to rather small amplitudes.

With respect to meso-scale disturbances, the above amplitudes seem somewhat more liberal. A surface

pressure disturbance of greater than 4 mb. is probably not greatly exceeded even in a squall line or hurricane convective band.

We now consider the nonlinear vertical heat transport by the linear disturbance solutions. In the present system heat energy is equal to $(c_p/R)\alpha p$.

After multiplication of (61) by $(c_p/R)p$ and integration over a horizontal distance X, we obtain the expression for average vertical transport:

$$\frac{\partial \overline{Q}}{\partial t} \approx \frac{c_p}{R}\frac{1}{X}\int_0^X p\frac{\partial \alpha'}{\partial t}dx = -\frac{c_p}{RX}\left[\int_0^X p\frac{\partial}{\partial p}(\alpha\omega)dx + p\alpha u\Big|_0^X\right] \tag{62}$$

where the compressibility terms have again been neglected.

If X is large or the disturbance is bounded, as in type II, case 2, the end-point term may be neglected. The term $\alpha\ \omega$ has opposite signs in the moist and dry regions but the integral is dominated by the contributions from the moist unstable region and is negative, with a maximum in the mid-troposphere. Thus for type II solutions $\partial\overline{Q}/\partial t \propto p \sin\frac{2\pi p}{p_0}$; that is, a net transfer of heat from the lower to the upper levels.

10. SUMMARY AND CONCLUSIONS

Solutions to a complete set of linearized quasi-static meteorological equations under conditions of moist parcel instability have been obtained and investigated. The assumptions made, besides the usual perturbation requirements, included zero basic flow at all levels. constant Coriolis parameter, no orography, and upward motion always saturated and downward motion either completely unsaturated or completely saturated.

The solutions obtained are essentially internal gravitational waves, their dynamic stability criterion depending upon the horizontal and vertical scales of motion, the value of the Coriolis parameter, the static stability for dry and moist motions and its vertical variation, and surface frictional drag and/or forced ascent. Unstable motions exist for horizontal scales of motion smaller than a limiting radius of several hundred kilometers, and the maximum growth rate occurs for disturbances whose horizontal extent is about the same as, or smaller than, their height. The conclusion that cloud-scale motions grow more rapidly than those of meso- or cyclone-scale obviously does not preclude the existence of the latter, but relegates their explanation to methods not used in this study. It appears, further, that the smaller-scale motions, because of their compensating dry downdraft regions, tend to discourage development of larger-scale disturbances unless, or until an organized meso-scale or large-scale ascending core can be established by nonconvective processes.

A number of disturbance models, differing in the arrangement of moist and dry regions, boundary conditions, and the vertical static stability distribution were investigated, and the effects on dynamic stability expressed in terms of an effective static stability. It was found that the existence of a dry stable region with descending motions surrounding a moist ascending center (type II, case 1) decreases the effective instability in comparison with that of a disturbance where both ascent and descent are moist unstable. A dry downdraft or "eye" in the center (case 3) exerts little influence, while regions of bands of alternating moist updraft and dry downdraft (case 4) have effects midway between those of each of the two components. Motions are very rapidly damped above a tropopause or base of a stable layer (type III, cases 1 and 2), and the latter acts effectively as a solid surface.

The lower boundary condition used generally was that $\omega=0$ at $p=p_0$, but replacement of this condition by one more closely akin to the true atmospheric boundary condition had very little effect on results.

The effects of surface friction were evaluated in a rather crude fashion, and results indicate that instability is increased somewhat by this effect for cyclone-scale disturbances, and that the maximum possible disturbance size increases considerably.

It was shown that an internally self-consistent energy equation can be written in which, disregarding friction, the sum of the productions of kinetic and available potential energy is equal to the heat released by condensation. Analysis of this energy equation shows that most of the kinetic and potential energy is released in the outer descending region despite its origin in the heat released in the inner ascending region. The mechanical efficiency of the system was found to be several times higher than that of observed tropical cyclones.

Finally, the effects of nonlinear terms in the primitive equations and energy equations were considered. It was found that disturbances of cyclone scale are essentially nonlinear almost as soon as detectable, but meso-scale motions maintain their linear character somewhat longer. The nonlinear terms of the cyclone-scale disturbances tended to bring the linear disturbances into closer agreement with observed structure. Further, these nonlinear terms yield a second-order stability criterion which permits subsequent deepening of a small-amplitude disturbance when the horizontal dimensions are only slightly smaller than the critical (vanishing linear growth rate) size; that is, for disturbances of the observed scale of tropical cyclones.

The results of this study fully corroborate Malkus and Riehl's [14] recent work indicating that further significant progress toward solution of the problem of tropical cyclogenesis will require more detailed knowledge of the dynamics, thermodynamics, and perhaps hygro-kinematics of cloud-scale and meso-scale convection. The smaller-scale convective processes tend to hinder cyclone development, both by the disruptive effects of dry downdrafts

surrounding the updraft elements, and by the stabilization due to their nonlinear heat transports. These effects alone may be sufficient to limit development of tropical cyclones to areas and periods when strong forcing disturbances cause general ascent and moistening of a substantial area.

ACKNOWLEDGMENTS

The author wishes to express his sincere thanks to Prof. Seymour L. Hess for his valuable suggestions and criticisms, and to Drs. J. Smagorinsky and S. Manabe, whose suggestions and encouragements were exceptionally helpful. The research described in this paper was begun at Florida State Universtity with support by the U.S. Weather Bureau under Contracts Nos. Cwb–9395 and Cwb–9683 and was completed at the U.S. Weather Bureau, General Circulation Research Section.

REFERENCES

1. L. Berkofsky, A Numerical Model for the Prediction of Hurricane Formation, Unpublished thesis, Massachusetts Institute of Technology, 1957.
2. J. Bjerknes, "Saturated-Adiabatic Ascent of Air Through Dry-Adiabatically Descending Environment," *Quarterly Journal of the Royal Meteorological Society*, vol. 64, No. 275, Apr. 1938, pp. 325–330.
3. J. G. Charney and A. Eliassen, "A Numerical Method for Predicting the Perturbations in the Middle-Latitude Westerlies," *Tellus*, vol. 1, No. 2, May 1949, pp. 38–54.
4. A. Eliassen, "The Quasi-Static Equations of Motion with Pressure as an Independent Variable," *Geofysiske Publikasjoner*, vol. 17, No. 3, 1949, 44 pp.
5. F. Frankl, "On Cauchy's Problem for Partial Differential Equations of Mixed Elliptico-Hyperbolic Type with Initial Data on the Parabolic Line," *Izvestiīā Akademii Nauk SSSR, Seriīā Matematicheskaīā*, vol. 8, 1944, pp. 195–224.
6. S. A. Gill, "A Process for the Step-by-Step Integration of Differential Equations in an Automatic Digital Computing Machine," *Proceedings, Cambridge Philosphical Society*, vol. 47, 1951, pp. 96–108.
7. C. L. Godske, T. Bergeron, J. Bjerknes, and R. C. Bundgaard, *Dynamic Meteorology and Weather Forecasting*, American Meteorological Society, Boston, Mass., 1957, 800 pp.
8. S. M. A. Haque, "The Initiation of Cyclonic Circulation in a Vertically Unstable Stagnant Air Mass," *Quarterly Journal of the Royal Meteorological Society*, vol. 78, 1952, pp. 394–406.
9. B. Haurwitz, "The Height of Tropical Cyclones and of the 'Eye' of the Storm," *Monthly Weather Review*, vol. 63, No. 2, Feb. 1935, pp. 45–48.
10. G. Hollmann, "Zur Frage der Lärmfilterung in den Hydro-Thermo-Dynamischen Gleichungen," *Beiträge zur Physik der Atmosphäre*, vol. 31, No. 1/2, 1958, pp. 5–30.
11. L. A. Hughes, "On the Low-Level Wind Structure of Tropical Storms," *Journal of Meteorology*, vol. 9, No. 6, Dec. 1952, pp. 422–428.
12. C. L. Jordan, "Mean Soundings for the West Indies Area," *Journal of Meteorology*, vol. 15, No. 1, Feb. 1958, pp. 91–97.
13. E. N. Lorenz, "Available Potential Energy and the Maintenance of the General Circulation," *Tellus*, vol. 7, No. 2, May 1955, pp. 157–167.
14. J. Malkus and H. Riehl, "On the Dynamics and Energy Transformations in Steady-State Hurricanes," *National Hurricane Research Project Report* No. 31, 1959, 31 pp.
15. W. V. L. Malkus and G. Veronis, "Finite Amplitude Cellular Convection," *Journal of Fluid Mechanics*, vol. 4, 1958, pp. 225–260.
16. T. Ootani and H. Hatakeyama, "Upper Air Current in the Typhoon," *Geophysical Magazine*, vol. 6, 1932, pp. 97–122.
17. E. Palmén, "Vertical Circulation and Release of Kinetic Energy During the Development of Hurricane Hazel into an Extratropical Storm," *Tellus*, vol. 10, No. 1, Feb. 1958, pp. 1–23.
18. E. Palmén and C. L. Jordan, "Note on the Release of Kinetic Energy in Tropical Cyclones," *Tellus*, vol. 7, No. 2, May 1955, pp. 186–188.
19. N. A. Phillips, "Numerical Integration of the Primitive Equations on the Hemisphere," *Monthly Weather Review*, vol. 87, No. 9, Sept. 1959, pp. 333–345.
20. J. Smagorinsky, "On the Numerical Integration of the Primitive Equations of Motion for Baroclinic Flow in a Closed Region," *Monthly Weather Review*, vol. 86, No. 12, Dec. 1958, pp. 457–466.
21. S. Syōno, "On the Formation of Tropical Cyclones," *Tellus*, vol. 5, No. 2, May 1953, pp. 179–195.
22. S. Syōno, Y. Ogura, K. Gambo, and A. Kasahara, "On the Negative Vorticity in a Typhoon," *Journal of the Meteorological Society of Japan*, Series 2, vol. 29, No. 12, Dec. 1951, pp. 397–414.
23. G. N. Watson, *A Treatise on the Theory of Bessel Functions*, 2d ed., University Press, Cambridge, Mass., 1944, 804 pp.

WEATHER NOTE

PRESSURE RISE AT YAKUTAT, DECEMBER 18, 1959

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Mr. Albert T. Gorman, observer in charge at Yakutat, Alaska, has brought to our attention a phenomenal pressure rise that occurred in a 3-hour period at Yakutat on December 18, 1959. Figure 1 is a reproduction of the station's barograph trace for the period 0800 AST December 17 to 0500 AST December 20, showing the spectacular pressure change.

Mid-December 1959 was a period of marked cyclonic activity in the Gulf of Alaska with a series of closely spaced, moderately intense storms, each having a central pressure of 970 to 980 mb. On the morning of December 17, the storm with which the pressure rise was associated was located 425 nautical miles southeast of stationary weather ship 4YP, and had shown a movement eastward at 20 to 25 knots in the previous 24 hours. At this time it turned northward into the Gulf of Alaska and by late afternoon (Dec. 17) was located 300 miles east of 4YP. By 0200 AST, December 18, the central pressure of the storm was 974 mb. and it was centered 175 miles west of Annette, Alaska. An associated cold front aloft was on a line north-northeastward to the vicinity of Juneau, while a sharp surface trough with the surface occluded front was on a line from the Low eastward to Annette and moving northward at 35 knots. Following the surface frontal passage, the surface pressure rose 10 mb. in 3 hours at Annette, and 13 mb. at Sitka in a similar period, with a rise of over 5 mb. in 1 hour.

The most astonishing pressure change occurred at Yakutat with a rise from 29.30 in. (983 mb.) at 1155 YST (1055 AST) December 18 to 29.575 in. (1001.5 mb.) at 1455 YST (1355 AST) December 18—a rise of 18.5 mb. in 3 hours and 11.1 mb. in a single hour. This may well be unique as the greatest hourly surface pressure rise associated with an extratropical storm trough on record. We would be interested to hear of any other extratropical surface pressure rises of similar or greater magnitude.

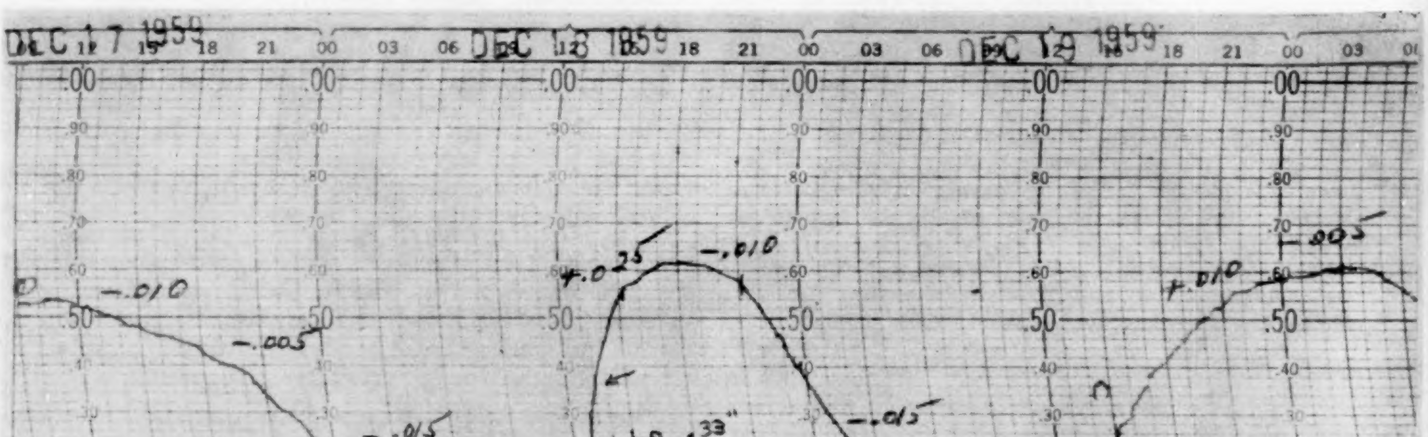

FIGURE 1.—Reproduction of section of barograph trace made at Yakutat, Alaska, 0800 AST December 17, 1959, to 0500 AST December 20, 1959. Note the exceptionally steep rise on the 18th.

THE WIND PROFILE AT THE CREST OF A LARGE RIDGE

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[Manuscript received September 9, 1959; revised December 21, 1959]

ABSTRACT

A set of observations of hourly wind movement at four levels in the layer 2–14 m. above the crest of a ridge is presented. The data are classified into prevailing wind types. During most periods the profile conforms to observations in flat terrain only in its lower part, and it does not conform to a normal structure of the free air. It is suggested that the observed profile represents an incompletely developed turbulent profile due to a short fetch over the ground surface.

1. INTRODUCTION

There have been a large number of investigations of the vertical profile of velocity near the ground, including many programs of measurements on towers or masts over flat or rolling terrain. There has been comparatively little in the way of precise observations above elevated terrain features.

The characteristics of the speed profile on ridge tops are of interest in regard to problems of anemometer exposure and comparison, and in relation to the general field of studies of the effect of topography on wind. In particular, it would be of interest to know the degree to which the profile resembles the profiles observed in flat terrain and the extent to which it varies with diurnal changes in thermal stability. Aerodynamic theory, as applied to the effects of topography, can be refined to more realistic models when the behavior in the "surface boundary layer" is known.

2. OBSERVATIONS AND ANALYSIS

In a field study in southwestern Washington, recorded data were obtained at levels 2.4, 4.0, 7.0, and 13.9 meters above the top of a ridge which is oriented north-south. The elevation of the ridge top is 875 m. and the local relief from valley to crest is about 450 m.; the ridge has the sharpest crest and the steepest slopes in the area. The site is near the foot of the western slope of the Cascade Range. Figure 1 shows the terrain profile near the crest. The pitch of the east-facing slope is quite similar to that of the west-facing slope. It is perhaps also of importance, in orienting this particular set of observations, to note that wind from almost all directions is subject to flow over other major ridges and valleys before reaching the site.

The ground cover varied from bare ground to bushes and bracken fern 0.5–1.0 m. in height, scattered clumps of trees about 3 m. in height, and a few conifers 9–15 m. The trees were not close enough to constitute obstructions to the instruments. Because of the irregular ground cover it is probably meaningless to define a friction surface.

Robinson three-cup anemometers were used. A comparison test was run with the anemometers side by side for a total of 1,600 km. of wind; the lowest and highest totals registered were within 3 percent of one another and no correction factors have been applied except for the standard calibration. There is a question of possible instrumental error due to nonhorizontal flow past the cups. The departure from the horizontal could not exceed the pitch of the ridge slopes, which is about 25°, and was probably much less. Wind tunnel tests [1, 2] have shown that errors in measurement of wind flow at incident angles of less than about 20° are negligible, and nonhorizontal flow is not considered to be a significant factor in the speed data obtained here.

Observations were recorded from September 15 to October 20, 1958. Direction recordings of 60 counts per

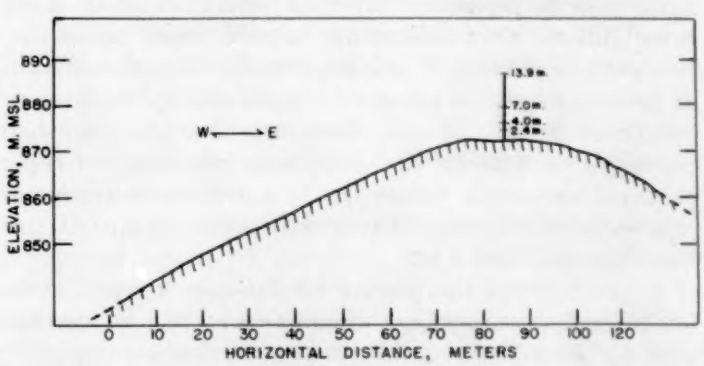

Figure 1.—Vertical section through the ridge near the crest. Vertical and horizontal scales are the same; the heights of anemometers are to scale.

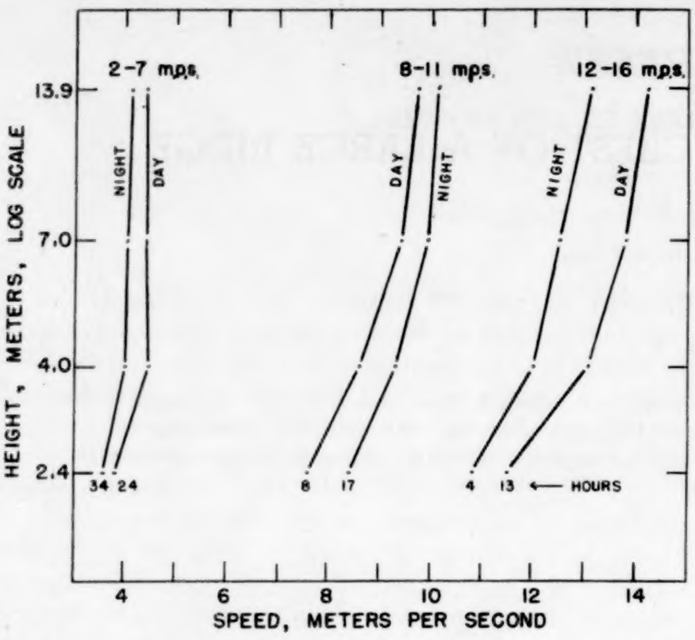

FIGURE 2.—Vertical profiles of speed at ridge top during fair-weather east winds (068°–113°).

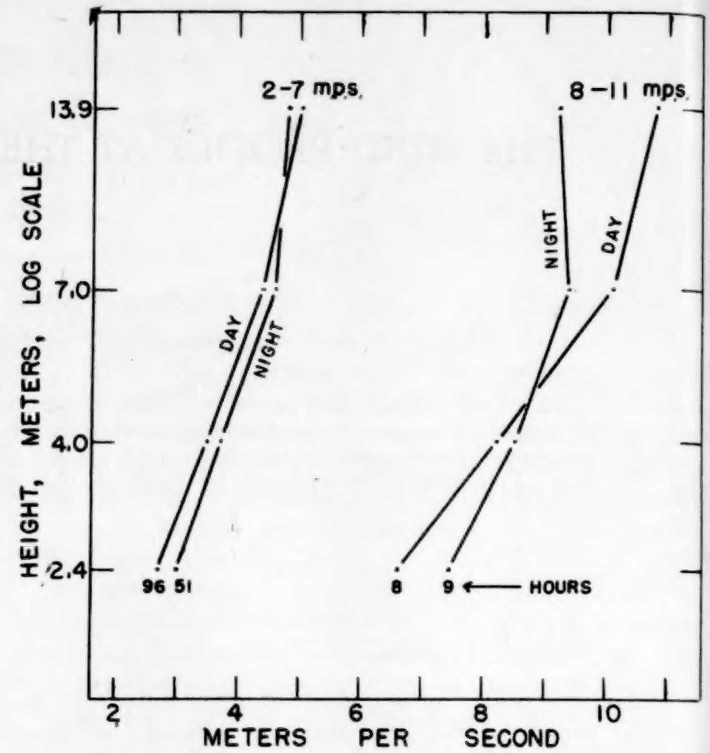

FIGURE 3.—Vertical profiles of speed at ridge top during fair-weather west winds (248°–293°).

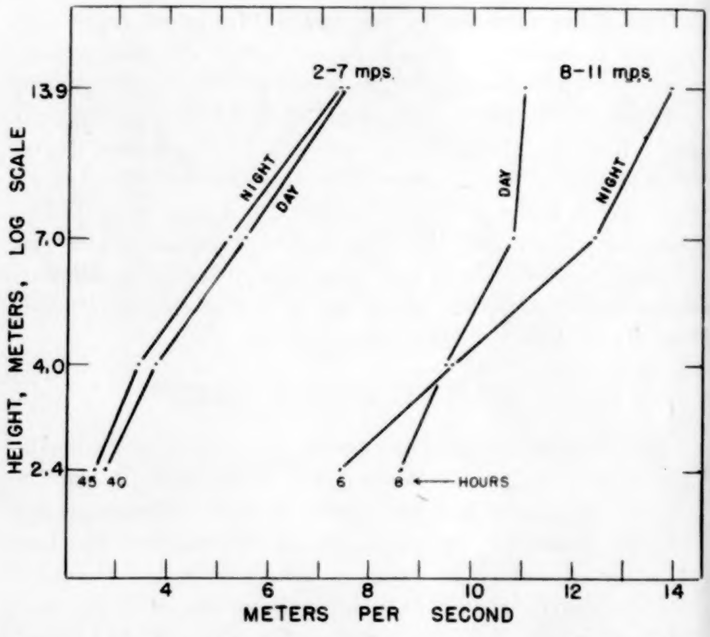

FIGURE 4.—Vertical profiles of speed at ridge top during rainy-weather westerly winds (203°–338°).

hour were obtained at the mast top. Frequent visual comparisons of directions at mast top and at 2.4 m. revealed no systematic variation. Speed data were tabulated as hourly totals of wind movement.

The data were separated into fair-weather periods and rainy periods. This selection is partly a subjective process, but the separation was considered desirable because rainfall has a pronounced effect on lapse rates and hence wind structure. The rainy periods consisted entirely of winds with a westerly component. The remaining westerly winds, classified as fair-weather winds, were sometimes accompanied by stratus or stratocumulus. The easterly winds, however, were accompanied by near-zero cloudiness. North and south winds were too light and infrequent to be representative and were discarded. The prevailing direction for each hour was tabulated to eight compass points. Hours when no single direction prevailed more than 50 percent of the time were discarded. Thus three general wind classes are treated: rainy westerlies, fair-weather westerlies, and fair-weather easterlies. Each of these is stratified by speed ranges and by daytime or nighttime hours. Hours when speeds were less than 2.2 m.p.s. at 4 m. on the mast were discarded in order to avoid erroneous values due to anemometer torque at near-calm conditions. The stratification of speeds was based on speeds at 4 m.

Figure 2 shows the profiles for the east winds. These are based on hours when the direction at 13.9 m. was due east. Figure 3 shows the profiles for fair-weather west winds. Prevailing northwest and southwest winds were treated separately, and although the hours of data are less the general features of the curves are similar. The data for daytime in the 8–11 m.p.s. range are almost entirely from one day and may not be a representative sample. In general, the shapes of the curves are similar to those for east winds, a principal difference being a greater slope within most of the strata (herein "greater slope" means greater increase of speed with height).

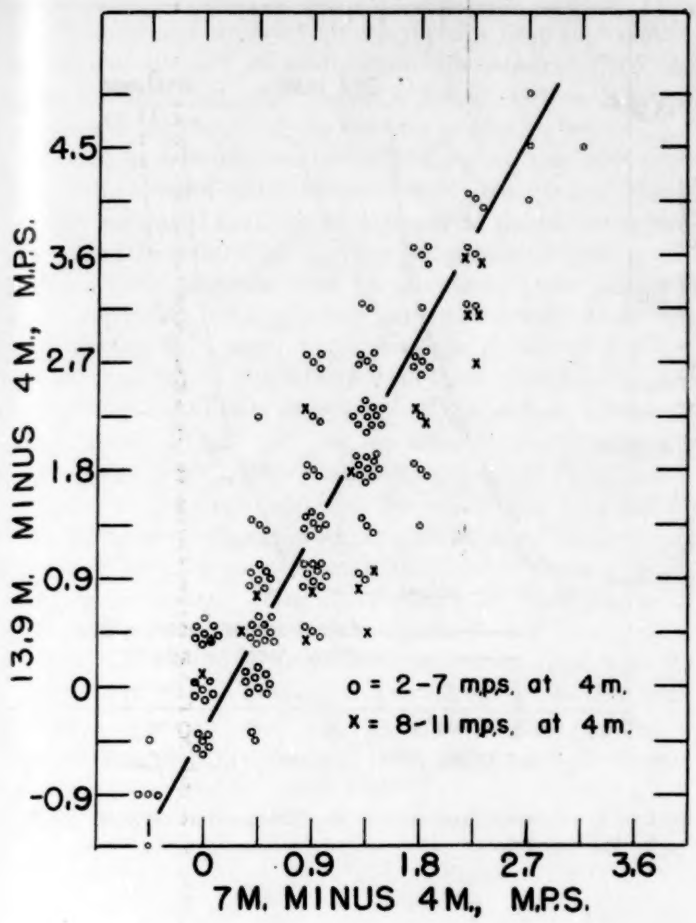

FIGURE 5.—Individual hourly differences in speed in the height interval 4.0–13.9 m. for fair-weather west winds.

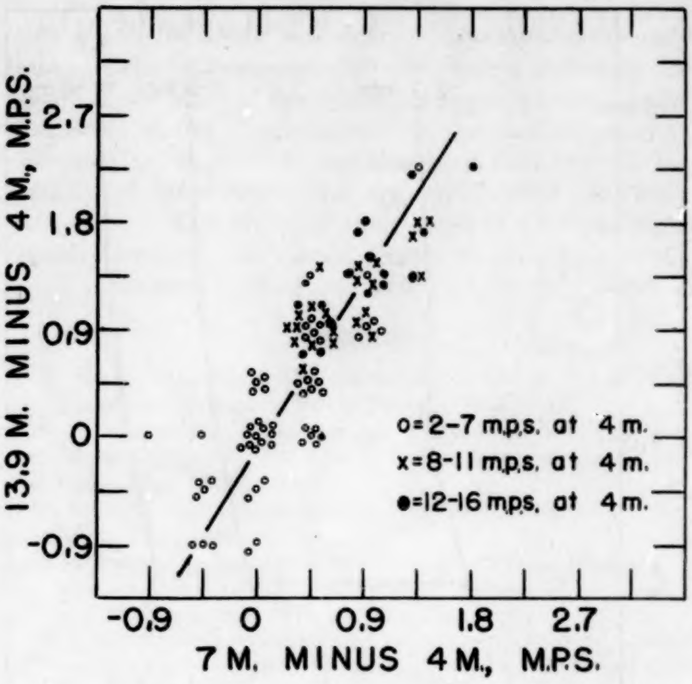

FIGURE 6.—Individual hourly differences in speed in the height interval 4.0–13.9 m. for fair-weather east winds.

One of the first characteristics noted in the profiles is the similarity between daytime and nighttime periods in most cases. This suggests that diurnal stability variations play a less important role in such an exposure than in plains and valleys.

The profiles for the rainy periods are shown in figure 4. In this classification, prevailing directions were west 50 percent, southwest 48 percent, and northwest 2 percent. Stratification into west and southwest directions showed no significant differences. The profiles are observed to have a greater slope than those of fair-weather west and east winds, and to have a curvature which is concave to the speed axis in the 2.4- to 7-m. height interval.

Figures 2–4 present mean profiles, but it is also desirable to illustrate the scatter about the mean. A test of this was arranged by tabulating the hourly differences in speed between 4 m. and 7 m. and between 4 m. and 13.9 m. These tabulations, along with the speed at 4 m., of course, represent the individual hourly profiles between 4 m. and 13.9 m. Figure 5 is a scatter diagram of these differences for the fair-weather west winds. The regression line is drawn by the graphical method. Figure 6 shows a similar plot for the east wind data.

These diagrams can be interpreted as follows. As one moves upward along the regression line, a greater slope (greater gradient in speed) is indicated. At the lower end are a few cases of reversed slope resulting from less speed at 13.9 m and 7 m. than at 4 m. Moving at right angles to the regression line, the area to the left indicates less (concave-upward) curvature in the profile and the area to the right greater curvature. Since the scatter is much larger along the regression line than at right angles to it, it can be seen that the curvature is a more conservative property than the slope.

3. DISCUSSION

If the air stream over the crest had the same structure as that of the free air, implying infinite shear at the ridge line, we would expect to observe a nearly constant speed in the vertical. Even if an extreme shear in the free air is taken, say 5 m.p.s. per 100 m., this would be equivalent to only 0.7-m.p.s. difference in the interval 4 to 13.9 m.; normally it would be much less. This nearly constant speed is only characteristic of the speed class 2–7 m.p.s. in the east winds.

The question naturally arises as to whether or not the observed profile is identical with the fully turbulent logarithmic or power-law profiles, observed over flat terrain under conditions of small temperature gradient. A graph of speed on a linear scale and height on a logarithmic scale should result in a straight-line plot if the data conform to the logarithmic law. Figures 2–4 show that the straight-line relationship does not hold too well,

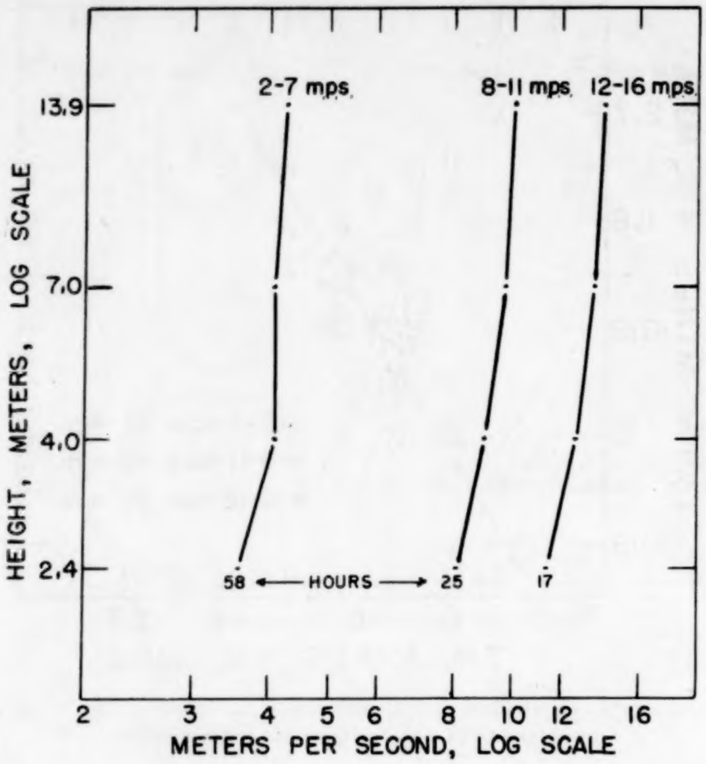

FIGURE 7.—Vertical profiles of east-wind speed at ridge top, on log-log coordinates. Day and night hours are combined.

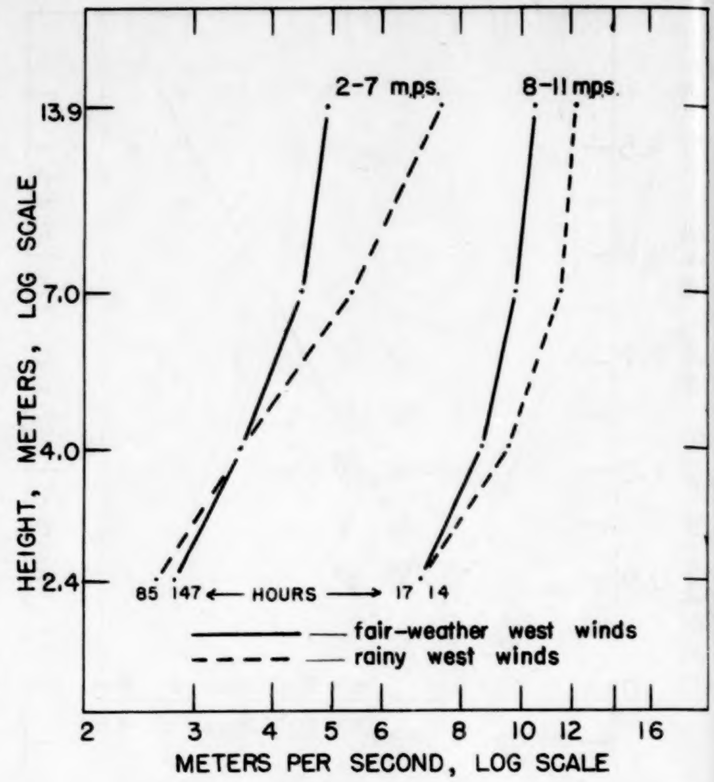

FIGURE 8.—Vertical profiles of west-wind speed at ridge top, on log-log coordinates. Day and night hours are combined.

especially in comparing the 2.4–4-m. layer with the layers above.

The simple form of the logarithmic law assumes a condition of neutral stability and might not be expected to apply to conditions on a ridge top. Theoretical extensions of the law to other condftions of lapse rate show that a profile curve which is convex toward the speed axis, as in figures 2–4, is typical of super-adiabatic lapse rates [3]. This is supported by observations, for example, by Johnson [4]. However, lapse rates on the ridge, if not neutral, would be expected to occur more frequently in the stable category than in the unstable one, favoring a profile concave toward the speed axis. Most of the profiles in figures 2–4 are convex toward the speed axis.

A power law has been found to fit observed data by several investigators. DeMarrais [5] has presented a comparison of the logarithmic and power laws in layers above the lowest few meters. His results favor the power law. It is usually expressed as

$$u=u_1\left(\frac{z}{z_1}\right)^a$$

where u_1 is a given speed at height z_1; the exponent a is assigned values appropriate to a particular investigation and is shown to vary with stability and other factors. A plot of log u against log z should result in a straight line if the power law holds. The factor a must be constant with height in order for a straight-line plot to result. The changes in the value of a with height which have been determined [5] are very small related to the height interval here, so we should expect a straight-line plot if the wind over the ridge has the same structure as that over flat terrain. Figure 7 shows the data for the east winds plotted on log-log coordinates. Again the straight-line relationship does not hold too well, although the fit is better than in figure 2.

The primary evidence that the profile does not correspond to that over flat terrain is provided by the value of the exponent a. In the layer 4–13.9 m. the mean value of a from figure 7 is near 0.07, a value significantly less than values obtained over flat surfaces, which range from about 0.10 to 0.75. This discrepancy does not appear in such clear-cut fashion in the west wind data nor in the layer 2.4–4 m. in any of the profiles. Within the layer 2.4–4 m., and at times in the layer 4–7 m., the value of a does lie within the range obtained in observations over flat terrain.

In this connection a statement by Rossby and Montgomery [6] is of interest: "It is probable that the z_0 value

determining the velocity profile in the first few meters above the surface depends upon the character of the ground within, say, the nearest hundred meters, whereas the z_0 value determining the velocity profile higher up . . . presumably depends on the character of the landscape over a distance of many kilometers." Rossby and Montgomery supposed that the adjustment of the mixed layer's depth to the effect of varying roughness is rapid. It appears quite possible that an air stream which strikes a rough surface after having been previously *above* the surface boundary layer requires some period of time of the order of a few minutes to develop a turbulent profile to the height normally attributed to the surface boundary layer (about 30 m.). If the air stream approaching the slope of the ridge is characterized by vertical shear below the level of the crest and also by converging trajectories toward the crest, then the upper part of the current would not have been in contact with the ground surface in its immediate history. The lower part may have had only a short fetch of some tens of meters over the ground surface. There may then be insufficient time for the turbulent profile to develop to its full extent by the time it moves over the crest. It is suggested that this is the explanation of the different characteristics of the lower and upper parts of the 13.9-m profile.

Knowledge of the profile of the incoming wind in a deep layer upstream, along with temperature lapse-rate conditions, would be necessary for establishing definitely the nature of the effect of the ridge. It appears quite possible that some of the characteristics of the profiles could be explained by a jet over the ridge, or that the vertical gradient of speed represents a simple barrier—or obstacle—effect. With either of these cases as a *unique* explanation, however, one should expect to observe a profile which is concave to the speed axis.

REFERENCES

1. W. E. K. Middleton, *Meteorological Instruments*, 2d ed. rev., University of Toronto Press, Toronto, 1943.
2. S. P. Fergusson, "Experimental Studies of Anemometers," *Harvard Meteorological Studies* No. 4, Harvard Univ. Press, Cambridge, Mass., 1939.
3. O. G. Sutton, *Micrometeorology*, McGraw-Hill Book Co., New York, N.Y., 1953, 333 pp.
4. O. Johnson, "An Examination of the Vertical Wind Profile in the Lowest Layers of the Atmosphere," *Journal of Meteorology*, vol. 16, No. 2, Apr. 1959, pp. 144–148.
5. G. A. DeMarrais, "Wind-Speed Profiles at Brookhaven National Laboratory," *Journal of Meteorology*, vol. 16, No. 2, Apr. 1959, pp. 181–190.
6. C. G. Rossby and R. B. Montgomery, "The Layer of Frictional Influence in Wind and Ocean Currents," Massachusetts Institute of Technology and Woods Hole Oceanographic Institution, *Papers in Physical Oceanography and Meteorology*, vol. 3, No. 3, 1935.

Publications by Weather Bureau Authors

J. K. ANGELL, "Lagrangian Wind Fluctuations at 300 mb. Derived from Transosonde Data," *Journal of Meteorology*, vol. 15, No. 6, Dec. 1958, pp. 522–530.

J. K. ANGELL, "The Use of Transosonde Data as an Aid to Analysis and Forecasting during the Winter of 1958–1959," *Journal of Geophysical Research*, vol. 64, No. 11, Nov. 1959, pp. 1845–1853.

E. M. BALLENZWEIG, "A Practical Equal-Area Grid," *Journal of Geophysical Research*, vol. 64, No. 6, June 1959, pp. 647–652.

R. G. BEEBE, "Tornadoes During 1958," *Weatherwise*, vol. 12, No. 1, Feb. 1959, pp. 13–15.

D. I. BLUMENSTOCK, "Typhoon Effects at Jaluit Atoll in the Marshall Islands," *Nature*, vol. 182, No. 4645, Nov. 8, 1958, pp. 1267–1269.

G. W. BRIER and D. B. KLINE, "Ocean Water as a Source of Ice Nuclei," *Science*, vol. 130, No. 3377, Sept. 18, 1959, p. 717.

D. COLSON, "Thunderstorm Analysis in the Northern Rocky Mountains," U.S. Dept. of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, *Research Paper*, No. 49, Ogden, Utah, 1957.

L. F. CONOVER [with H. W. Hiser and H. V. Senn], "Rainfall Measurement by Radar Using Photographic Integration Techniques" *Transactions*, American Geophysical Union, vol. 39, No. 6, 1958, pp. 1043–1047.

I. ENGER, "Optimum Length of Record for Climatological Estimates of Temperature," *Journal of Geophysical Research*, vol. 64, No. 7, July 1959, pp. 779–787.

R. FAY, "A Note on the Mid-Tropospheric Wind Maximum," *Bulletin of the American Meteorological Society*, vol. 39, No. 7, July 1958, pp. 360–362.

H. FOSTER, "Critical Problems in RADU," *Proceedings of 6th Weather Radar Conference*, Cambridge, Mass., Mar. 26–28, 1957, pp. 367–368.

S. FRITZ, "On the 'Arctic Whiteout'," *Polar Atmosphere Symposium Part I Meteorology Section*, Pergamon Press, 1958, pp. 182–186.

S. FRITZ, "Solar Radiation Measurements in the Arctic Ocean," *Polar Atmosphere Symposium Part I Meteorology Section*, Pergamon Press, 1958, pp. 159–166.

J. R. FULKS, "Review of *The Real Book about the Weather*, Frank Forrester, Doubleday & Co., Inc., New York, 1959," *Bulletin of the American Meteorological Society*, vol. 40, No. 11, Nov. 1959, p. 583.

F. GIFFORD, "Statistical Mechanics and Theoretical Models of Diffusion Processes," "Proceedings of Symposium on Atmospheric Diffusion and Air Pollution, held at Oxford, August 1958," *Advances in Geophysics*, vol. 6, 1959, Academic Press, New York, pp. 117–137.

W. H. HAGGARD, "Where Hurricanes Begin," *Weatherwise*, vol. 12, No. 4, Aug. 1959, pp. 145–150.

W. H. HOECKER, "History and Measurement of the Two Major Scottsbluff Tornadoes of 27 June 1955," *Bulletin of the American Meteorological Society*, vol. 40, No. 3, Mar. 1959, pp. 117–133.

G. C. HOLZWORTH, "Atmospheric Contaminants at Remote California Coastal Sites," *Journal of Meteorology*, vol. 16, No. 1, Feb. 1959, pp. 68–79.

L. A. JOOS, "The Midwinter Storm in Illinois," *Weatherwise*, vol. 12, No. 2, Apr. 1959, pp. 47–48.

H. E. LANDSBERG, "Data Processing in Geophysics," *Contributions in Geophysics*, in honor of Beno Gutenberg, 1957.

H. E. LANDSBERG, "Preparing Climatic Data for the User," WMO *Technical Note*, No. 22, 1958.

R. A. MCCORMICK, [with C. H. B. Priestley and F. Pasquill] "Turbulent Diffusion in the Atmosphere," WMO *Technical Note* No. 24, Geneva 1958, 68 pp.

L. MACHTA, "Transport in the Stratosphere and Through the Tropopause," "Proceedings of Symposium on Atmospheric Diffusion and Air Pollution, held at Oxford, August 1958," *Advances in Geophysics*, vol. 6, 1959, Academic Press, New York, pp. 273–286.

J. M. Mitchell, Jr., "The Weather and Climate of Alaska," *Weatherwise*, vol. 11, No. 5, Oct. 1958, pp. 151–160.

R. H. NOLEN, "A Radar Pattern Associated with Tornadoes," *Bulletin of the American Meteorological Society*, vol. 40, No. 6, June 1959, pp. 277–279.

A. SADOWSKI, "Coastal Storm on Cape Hatteras Radar, October 5–6, 1957," *Weatherwise*, vol. 12, No. 3, June 1959, pp. 111–113.

W. W. SHINNERS, "The U.S. Weather Bureau Transient Ship Upper-Air Program," *Weatherwise*, vol. 11, No. 4, Aug. 1958, pp. 124–125.

E. C. THOM, "The Discomfort Index," *Weatherwise*, vol. 12, No. 2, Apr. 1959, pp. 57–60.

L. L. WEISS and W. T. WILSON, "Snow-Melt Degree-Day Ratios Determined from Snow-Lab Data," *Transactions*, American Geophysical Union, vol. 39, No. 4, Aug. 1958, pp. 681–688.

H. WEXLER, "IGY Meteorology in Antarctica," *Weatherwise*, vol. 11, No. 4, Aug. 1958, p. 115.

NOTE: In the list published in the November 1959 issue, p. 426, the entry under J. T. Lee is in error. It should read: A. Sadowski, (In collaboration with staff of Severe Local Storm Forecast Center, Kansas City) "Forecasting Tornado Possibilities," *Weatherwise*, vol. 11, No. 2, Apr. 1958, pp. 51–54.

MEAN MONTHLY VALUES OF PRECIPITABLE WATER OVER THE UNITED STATES, 1946–56[1]

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ABSTRACT

Mean monthly values of precipitable water have been computed for radiosonde stations in the United States for the period 1946–56. The individual monthly values and an elementary statistical analysis are presented for 52 stations with data during all or part of the period.

1. INTRODUCTION

Precipitable water is a measure of the moisture content of the air and can be expressed as the depth to which liquid water would stand over a unit area if all the water vapor in a column from the surface to some upper level were condensed. Solot [1] has presented a derivation of an expression for precipitable water. Since precipitable water is an expression for the total amount of moisture in the air, it is used in forecasting or as a research tool whenever such a measure is needed. Despite its increasing application, little information about its magnitude is found in the literature. Shands [2] using data compiled by Ratner [3] published values of mean monthly precipitable water for 29 stations in the United States. The length of record was about 4 years for most of the stations. Since that time, few data of that type have been published.

The Institute of Atmospheric Physics of the University of Arizona has computed mean monthly values of precipitable water for 52 radiosonde stations, most of which are in the continental United States. The stations are listed in table 1 and their locations are shown in figure 1. In general, the length of record is 11 years, from 1946 through 1956. These computations were begun in 1957 in answer to a request for mean monthly precipitable water data for use by research groups at the University of Chicago. At that time, values were computed for 46 stations for a 3-year period, 1954–56. Since these original computations were made, additional mean monthly radiosonde data on IBM punchcards have been received and computations made. This report summarizes and presents the mean monthly values of precipitable water that have been computed.

[1] The work reported here was supported by the Office of Naval Research under contract No. ONR 2173-02.

2. DESCRIPTION OF THE COMPUTATIONS

The data used in these calculations were mean monthly radiosonde data on IBM punchcards obtained from the National Weather Records Center in Asheville, N.C. The cards contain the mean temperature, relative humidity, and height (mean pressure for surface observations) of pressure surfaces at 50-mb. intervals beginning at the surface, then 1,000 mb. The 50-mb. level at which temperature and relative humidity values begin is governed by the elevation and surface pressure at each station. Precipitable water was computed from the surface to 325 mb. and was based primarily on radiosonde data taken at 0300 GMT.

The mean data utilized in computing precipitable water are the temperature and relative humidity. The expression evaluated was

$$W=\frac{10^3\epsilon}{g}\frac{e_sU}{p}\Delta p$$

where W=precipitable water (cm.)

ϵ=ratio of the molecular weight of water vapor to that of dry air

g=acceleration of gravity (cm. sec.$^{-2}$)

e_s=saturation vapor pressure (mb.) determined using the mean temperature

U=relative humidity

p=pressure (mb.) at the point of observation

Δp=depth of the layer (mb.) surrounding the point of observation, usually 50 mb.

TABLE 1.—*List of station names and numbers for which calculations of mean monthly precipitable water were made, and the number of months of record*

No.	Station Name	Number of months	No.	Station Name	Number of months
14735	Albany	86	13963	Little Rock	132
23050	Albuquerque	132	22009	Mazatlan	83
26409	Anchorage	96	24225	Medford	132
24011	Bismarck	132	12839	Miami	118
24131	Boise	132	23023	Midland	131
12919	Brownsville	132	14756	Nantucket	128
04738	Buffalo	132	13897	Nashville	126
12853	Burrwood	127	24023	North Platte	132
14607	Caribou	117	23230	Oakland	132
13880	Charleston	132	13967	Oklahoma City	132
13983	Columbia	131	94918	Omaha	101
13985	Dodge City	132	23183	Phoenix	132
23044	El Paso	131	94823	Pittsburgh	124
23154	Ely	132	14764	Portland	132
26411	Fairbanks	119	24090	Rapid City	132
13911	Fort Worth	105	14926	St. Cloud	124
23066	Grand Junction	132	12921	San Antonio	132
24143	Great Falls	132	93112	San Diego	126
13723	Greensboro	132	11636	San Juan	119
11706	Guantanamo Bay	86	23273	Santa Maria	132
13745	Hatteras	119	14847	Sault Ste. Marie	132
12864	Havana	66	24244	Seattle	90
14918	International Falls	132	24157	Spokane	132
13941	Lake Charles	120	12842	Tampa	132
24021	Lander	132	24240	Tatoosh Island	132
23169	Las Vegas	132	93722	Washington, D.C	132

The expression results from the basic derivation and the usual assumption that there is no significant difference between the density of moist and dry air. The computations were made using an IBM–650 digital computer and supporting machines operated by the Numerical Analysis Laboratory of the University of Arizona.

The value of relative humidity was determined using both the actual observations and the statistical values of relative humidity. Statistical values are Weather Bureau estimates of relative humidity when "motorboating" occurs; that is, when the moisture content of the air is low, beyond the measuring capabilities of the humidity element. When the number of actual observations (Good Counts) is less than 15, the Weather Bureau does not compute a mean monthly value of relative humidity. However, in this study, relative humidity was computed using the actual observations and the statistical values even when the number of actual observations was below 15.

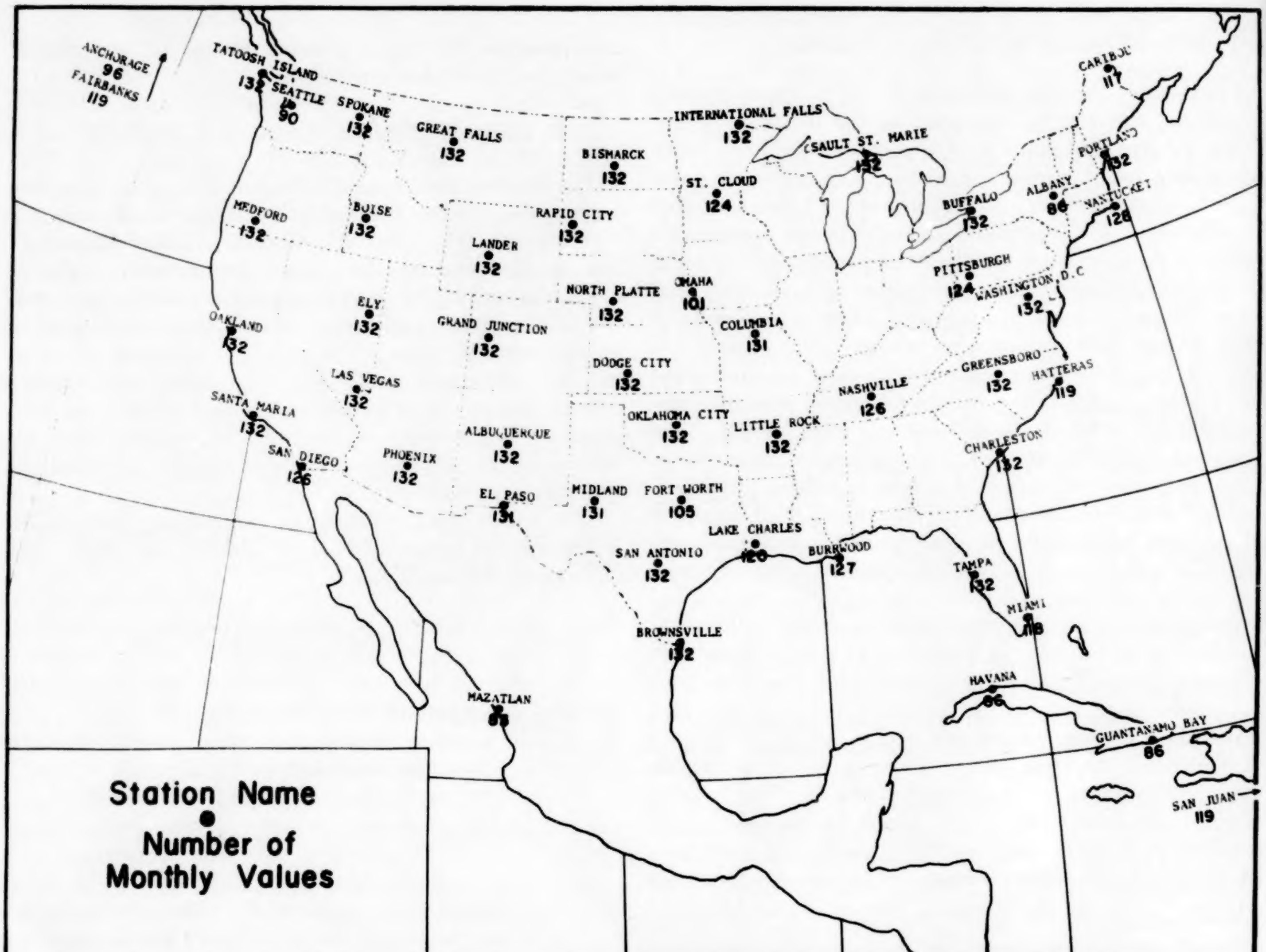

FIGURE 1.—Station names, locations, and number of months for which values of mean monthly precipitable water were computed.

TABLE 2.—*Mean monthly values of precipitable water (cm.) from the surface to 325 mb., computed using mean monthly radiosonde data. Standard deviations and coefficients of variation were computed for months with nine or more individual values of precipitable water. The yearly mean is the average of the 12 monthly values, not adjusted for variations in the length of the months.*

Albany : 14735 Sfc. Press. 1006 mb, Elev. 86 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946	0.69	0.56	1.07	1.09	1.95	2.41	2.96	2.70	2.45	1.93	1.20	0.81	1.65
1947	0.90	0.53	0.71	1.27	1.86	2.53	3.37	3.53	2.37	1.97	1.03	0.70	1.73
1948	0.54	0.55	0.86	1.30	2.00	2.57	2.98	2.93	2.09	1.44	1.65	0.77	1.62
1949	0.97	0.76	0.91	1.25	1.84	2.84	3.49	2.91	2.22	1.80	1.07	0.88	1.75
1950	1.10	0.67	0.68	0.99	1.75	2.51	2.74	2.82	2.15	1.69	1.24	0.75	1.59
1951	0.77	0.82	0.98	1.33	1.77	2.52	3.19	2.90	2.30	1.71	0.98		
1952													
1953													
1954													
1955										1.51	1.12	0.60	
1956	0.89	0.73	0.73	1.06	1.35	2.38	2.63	2.58	1.96	1.50	1.11	1.01	1.49
No.	7	7	7	7	7	7	7	7	7	8	8	7	
Mean	0.84	0.66	0.85	1.18	1.79	2.54	3.05	2.91	2.22	1.69	1.15	0.79	1.64
Std Dev σ													
C.V. (%)													

Bismarck : 24011 Sfc. Press. 955 mb; Elev. 505 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946	0.56	0.59	1.05	1.19	1.37	2.22	2.59	2.23	1.95	1.19	0.84	0.62	1.37
1947	0.59	0.44	0.55	1.03	1.28	2.25	2.53	2.76	1.90	1.64	0.63	0.67	1.36
1948	0.48	0.50	0.61	1.08	1.47	2.25	2.78	2.57	2.01	1.18	0.78	0.49	1.35
1949	0.49	0.48	0.67	0.99	1.76	2.11	2.67	2.50	1.55	1.32	0.94	0.54	1.33
1950	0.36	0.56	0.60	0.81	1.44	1.83	2.39	2.35	1.94	1.46	0.64	0.66	1.25
1951	0.44	0.61	0.49	0.81	1.36	1.85	2.51	2.55	1.73	1.32	0.67	0.46	1.23
1952	0.53	0.67	0.57	0.94	1.38	2.42	2.29	2.43	1.78	0.92	0.74	0.66	1.28
1953	0.71	0.60	0.75	0.84	1.52	2.32	2.43	2.64	1.64	1.38	0.99	0.68	1.37
1954	0.48	0.85	0.59	0.98	1.21	2.15	2.71	2.55	2.00	1.26	0.98	0.67	1.37
1955	0.55	0.48	0.52	1.15	1.67	2.18	2.94	2.74	1.75	1.22	0.60	0.57	1.36
1956	0.58	0.50	0.58	0.76	1.67	2.42	2.51	2.43	1.64	1.26	0.83	0.76	1.33
No.	11	11	11	11	11	11	11	11	11	11	11	11	11
Mean	0.53	0.57	0.64	0.96	1.47	2.18	2.58	2.52	1.81	1.29	0.79	0.62	1.33
Std Dev σ	0.08	0.12	0.15	0.14	0.18	0.19	0.19	0.15	0.16	0.18	0.15	0.09	0.04
C.V. (%)	16	20	24	15	12	9	7	6	9	14	19	15	3

Albuquerque : 23050 Sfc. Press. 837 mb, Elev. 1619 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946	0.61	0.55	0.71	1.10	1.04	1.39	2.31	2.60	2.03	1.17	0.85	0.76	1.26
1947	0.58	0.62	0.71	0.82	1.32	1.42	2.01	2.57	1.70	1.18	0.67	0.62	1.19
1948	0.66	0.75	0.64	0.90	1.27	1.84	2.08	2.40	1.72	1.21	0.64	0.75	1.24
1949	0.64	0.58	0.70	1.01	1.17	1.88	2.65	2.25	1.99	1.10	0.75	0.60	1.28
1950	0.55	0.72	0.55	0.77	0.83	1.33	2.45	1.92	1.59	1.15	0.65	0.56	1.09
1951	0.57	0.65	0.56	0.80	1.01	0.89	2.26	2.47	1.24	1.03	0.69	0.63	1.07
1952	0.66	0.53	0.62	0.95	1.16	1.67	2.22	2.57	1.45	0.79	0.69	0.60	1.16
1953	0.64	0.50	0.73	0.74	0.89	1.39	2.53	2.11	1.08	1.05	0.80	0.50	1.08
1954	0.62	0.53	0.63	0.81	1.32	1.22	2.47	2.29	2.00	1.23	0.70	0.57	1.20
1955	0.55	0.44	0.54	0.60	1.12	1.18	2.34	2.73	1.63	1.03	0.65	0.75	1.13
1956	0.75	0.50	0.48	0.65	0.90	1.75	2.28	2.04	1.29	1.06	0.52	0.52	1.06
No.	11	11	11	11	11	11	11	11	11	11	11	11	11
Mean	0.62	0.58	0.63	0.83	1.09	1.45	2.33	2.36	1.61	1.09	0.69	0.62	1.16
Std Dev σ	0.06	0.10	0.08	0.15	0.17	0.29	0.19	0.26	0.31	0.12	0.09	0.09	0.07
C.V. (%)	9	17	13	18	16	20	8	11	19	11	12	14	6

Boise : 24131 Sfc. Press. 915 mb, Elev. 868 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946	0.74	0.78	0.98	1.18	1.27	1.45	1.87	1.62	1.43	1.15	1.02	0.96	1.20
1947	0.67	0.95	1.05	1.09	1.57	1.63	1.52	1.44	1.55	1.56	1.01	0.91	1.25
1948	0.84	0.74	0.74	1.04	1.37	2.06	1.73	1.61	1.41	1.20	0.90	0.66	1.19
1949	0.42	0.68	0.92	1.00	1.51	1.51	1.57	1.78	1.56	1.09	1.29	0.76	1.17
1950	0.59	0.91	0.93	0.92	1.11	1.67	1.57	1.69	1.59	1.40	1.15	1.18	1.23
1951	0.76	0.85	0.76	0.96	1.29	1.33	1.67	1.67	1.12	1.23	0.96	0.76	1.11
1952	0.71	0.71	0.79	1.03	1.42	1.71	1.67	1.51	1.29	1.07	0.72	0.95	1.13
1953	1.10	0.79	0.90	0.90	1.16	1.49	1.45	1.65	1.42	1.28	1.21	0.89	1.19
1954	0.83	0.96	0.70	0.95	1.23	1.36	1.71	1.58	1.23	1.06	1.10	0.78	1.14
1955	0.70	0.63	0.68	0.96	1.16	1.55	1.82	1.29	1.38	1.20	0.89	0.86	1.09
1956	0.85	0.58	0.77	1.00	1.58	1.60	1.84	1.67	1.22	1.27	0.94	0.89	1.18
No.	11	11	11	11	11	11	11	11	11	11	11	11	11
Mean	0.75	0.78	0.84	1.00	1.33	1.60	1.68	1.59	1.38	1.23	1.02	0.87	1.17
Std Dev σ	0.17	0.13	0.13	0.08	0.17	0.18	0.13	0.13	0.15	0.15	0.16	0.14	0.04
C.V. (%)	23	16	15	8	12	11	8	8	11	12	16	16	4

Anchorage : 26409 Sfc. Press. 1003 mb; Elev. 30 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946	0.58	0.56	0.45	0.69	1.28	1.89	2.40	2.18	1.60	1.05	0.58	0.19	1.12
1947	0.12	0.67	0.84	0.72	1.13	1.52	2.06	1.77	1.61	1.04	0.95	0.73	1.10
1948	0.66	0.38	0.48	0.62	1.14	1.67	2.10	1.85	1.38	0.98	0.48	0.39	1.01
1949	0.56	0.39	0.80	0.72	1.09	1.50	2.02	2.03	1.71	0.94	0.84	0.64	1.09
1950	0.56	0.32	0.64	0.67	1.11	1.71	2.05	2.06	1.47	0.89	0.40	0.61	1.04
1951	0.38	0.54	0.39	0.89	1.14	1.76	2.30	2.25	1.68	0.76	0.79	0.48	1.11
1952	0.37	0.62	0.59	0.64	0.86	1.46	2.11	1.82	1.44	1.17	0.88	0.59	1.05
1953	0.39	0.57	0.47	0.81	1.13	1.87	2.06	2.09	1.42	0.78	0.64	0.64	1.07
1954													
1955													
1956													
No.	8	8	8	8	8	8	8	8	8	8	8	8	8
Mean	0.45	0.51	0.58	0.72	1.11	1.67	2.14	2.01	1.54	0.95	0.70	0.51	1.07
Std Dev σ													
C.V. (%)													

Brownsville : 12919 Sfc. Press. 1014 mb, Elev. 7 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946	2.31	2.62	2.37	3.13	4.04	3.99	3.97	3.90	4.92	3.88	3.39	2.54	3.42
1947	2.44	1.99	2.19	3.14	3.48	3.65	3.99	4.47	3.86	3.42	3.08	2.76	3.21
1948	2.24	2.70	2.69	2.30	3.73	3.69	4.52	4.26	4.11	3.55	2.81	2.73	3.29
1949	2.70	3.07	2.90	3.23	3.74	4.31	4.26	3.97	4.64	3.83	1.99	3.20	3.46
1950	2.92	2.76	2.72	3.34	3.98	3.90	4.13	3.95	4.20	3.28	2.41	1.88	3.29
1951	2.26	2.01	2.60	2.79	3.72	3.97	4.18	4.26	4.56	3.51	2.00	2.83	3.29
1952	2.54	2.17	2.66	2.86	3.02	4.17	4.16	3.98	3.73	1.99	2.89	2.37	3.04
1953	1.60	2.37	3.12	2.93	3.27	3.59	4.24	4.45	3.25	3.13	2.35	2.32	3.05
1954	2.42	2.20	2.34	3.18	3.21	3.84	4.09	4.14	4.27	3.57	2.43	2.03	3.14
1955	2.30	2.31	2.53	2.83	3.20	3.28	4.54	4.56	5.01	3.08	3.24	2.31	3.27
1956	2.11	2.54	2.45	2.99	3.41	3.96	4.04	4.11	3.71	3.26	2.56	2.42	3.13
No.	11	11	11	11	11	11	11	11	11	11	11	11	11
Mean	2.35	2.43	2.60	2.99	3.53	3.82	4.19	4.19	4.21	3.32	2.72	2.49	3.24
Std Dev σ	0.34	0.34	0.27	0.24	0.34	0.25	0.18	0.24	0.52	0.48	0.39	0.38	0.15
C.V. (%)	14	14	10	8	10	6	4	6	12	15	14	15	5

A limited amount of correction was made to these data to make the computations as complete as possible. In some instances, 1500 GMT data were substituted for the basic 0300 GMT data, a practice which does not introduce significant error. Published mean monthly radiosonde data from the *Monthly Weather Review* and *Climatological Data, National Summary* were used to correct and complete the data when appropriate. At temperatures

TABLE 2.—Continued.

Buffalo, N. Y. : 04738 Sfc. Press. 990 mb; Elev. 182 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946	0.66	0.63	1.19	1.02	1.70	2.31	2.49	2.43	2.21	1.85	1.30	0.76	1.55
1947	0.86	0.50	0.63	1.27	1.78	2.19	2.72	3.36	2.39	1.85	0.92	0.70	1.60
1948	0.47	0.64	0.91	1.40	1.69	2.46	2.91	2.56	2.15	1.39	1.36	0.77	1.56
1949	1.01	0.79	[illegible]	1.08	1.70	2.65	3.29	2.64	1.93	1.71	1.03	0.80	1.62
1950	1.00	0.66	0.71	0.98	1.68	2.23	2.62	2.68	2.25	1.77	1.12	0.67	1.53
1951	0.80	0.84	0.85	1.22	1.66	2.48	2.91	2.53	2.17	1.58	0.91	0.76	1.56
1952	0.80	0.68	0.81	1.32	1.61	2.54	3.01	2.61	2.12	1.24	1.18	0.91	1.57
1953	0.89	0.73	0.95	1.08	2.13	2.53	2.78	2.59	2.08	1.45	1.08	0.83	1.59
1954	0.65	0.79	0.69	1.42	1.41	2.87	2.58	2.67	2.35	1.99	1.09	0.75	1.60
1955	0.59	0.74	0.82	1.60	1.92	2.24	3.02	3.38	2.10	1.77	1.09	0.61	1.66
1956	0.82	0.74	0.68	1.07	1.60	2.47	2.78	2.78	1.83	1.61	1.10	1.04	1.54
No.	11	11	11	11	11	11	11	11	11	11	11	11	11
Mean	0.78	0.70	0.83	1.22	1.72	2.45	2.83	2.75	2.14	1.66	1.11	0.78	1.58
Std Dev σ	0.17	0.09	0.16	0.19	0.19	0.20	0.23	0.37	0.16	0.23	0.14	0.12	0.05
C.V.(%)	22	13	19	16	11	8	8	13	7	14	13	15	3

Charleston : 13880 Sfc. Press. 1016 mb; Elev. 13 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946	1.74	1.55	2.06	2.21	3.25	3.55	4.73	4.40	3.88	2.56	2.67	1.71	2.86
1947	2.24	0.99	1.31	2.77	2.86	3.59	4.12	4.58	3.96	3.26	2.18	1.82	2.81
1948	1.51	2.16	2.30	2.45	3.04	3.75	4.88	4.17	3.76	2.13	2.91	2.00	2.92
1949	2.28	2.13	1.81	2.23	3.04	4.34	4.42	4.71	3.78	3.39	1.55	1.72	2.95
1950	2.34	1.60	1.68	1.66	3.26	4.06	4.58	4.08	3.67	2.86	1.51	1.38	2.72
1951	1.40	1.40	1.86	2.00	2.48	3.80	4.43	4.44	4.09	3.11	1.82	1.74	2.71
1952	1.88	1.59	1.62	1.84	2.86	4.43	4.33	4.45	3.55	1.90	1.78	1.40	2.64
1953	1.57	1.75	1.91	1.90	3.00	3.81	4.43	4.09	3.63	2.37	1.73	1.74	2.66
1954	1.55	1.42	1.58	2.62	2.54	3.44	4.22	4.43	3.70	2.32	1.66	1.37	2.57
1955	1.46	1.50	1.96	2.16	3.02	3.08	4.22	4.52	4.39	2.38	1.66	1.52	2.66
1956	1.21	2.00	1.60	1.83	3.15	3.83	4.57	4.40	3.48	3.14	1.66	1.88	2.73
No.	11	11	11	11	11	11	11	11	11	11	11	11	11
Mean	1.74	1.65	1.79	2.15	2.96	3.79	4.45	4.39	3.81	2.68	1.92	1.66	2.75
Std Dev σ	0.39	0.35	0.27	0.35	0.25	0.39	0.23	0.20	0.26	0.49	0.47	0.21	0.12
C.V.(%)	22	21	15	16	9	10	5	5	7	18	24	13	4

Burrwood : 12863 Sfc. Press. 1017 mb; Elev. 3 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946		2.18					4.26	4.37	4.01	2.96	3.11	1.72	
1947	2.41	1.35	1.72	2.93	3.24	4.22	3.90	4.66	4.15	3.18	2.50	2.08	3.03
1948	1.78	2.41	2.70	2.55	2.97	3.83	4.54	4.52	3.84	2.29	2.70	2.24	3.03
1949	2.52	2.53	2.12	2.66	2.99	4.37	5.00	4.44	4.26	3.98	1.63	2.20	3.22
1950	2.92	2.18	1.96	2.28	3.41	4.11	4.58	4.50	4.07	2.91	1.95	1.88	3.06
1951	1.89	1.90	2.24	2.30	2.71	3.93	4.60	4.87	4.73	3.21	1.93	2.36	3.06
1952	2.38	2.10	2.10	2.04	3.01	4.01	4.26	4.61	3.99	1.72	2.08	2.20	2.87
1953	1.72	2.26	2.48	2.45	3.05	4.15	4.41	4.63	3.20	2.35	2.23	2.21	2.93
1954	1.92	1.71	1.90	2.84	2.64	3.78	4.67	4.13	3.90	2.96	1.93	1.71	2.84
1955	1.81	2.10	2.22	2.43	2.95	3.18	4.45	4.55	4.72	2.75	2.47	2.10	2.98
1956	1.61	2.36	2.26	2.31	3.36	3.45	4.04	4.06	3.61	2.89	1.90	2.16	2.83
No.	10	11	10	10	10	10	11	11	11	11	11	11	10
Mean	2.10	2.10	2.17	2.48	3.03	3.90	4.43	4.49	4.04	2.84	2.22	2.08	2.99
Std Dev σ	0.43	0.34	0.28	0.27	0.25	0.36	0.31	0.24	0.44	0.58	0.43	0.22	0.12
C.V.(%)	21	16	13	11	8	9	7	5	11	20	20	10	4

Columbia : 13983 Sfc. Press. 988 mb; Elev. 238 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946		0.79	1.55	1.79	2.19	2.88	3.39	3.27	2.72	1.91	1.51	1.12	
1947	0.93	0.58	0.86	1.78	2.09	3.43	3.00	4.10	2.63	2.41	1.19	0.96	2.00
1948	0.65	1.06	1.23	1.79	2.14	3.25	3.78	3.49	2.62	1.51	1.30	1.00	1.99
1949	1.11	0.94	1.14	1.45	2.52	3.77	4.36	3.36	2.18	2.04	1.07	0.95	2.07
1950	1.15	1.04	0.97	1.37	2.31	3.12	3.10	3.16	2.76	1.91	0.93	0.83	1.89
1951	0.78	1.16	1.08	1.37	2.06	3.21	3.70	3.37	2.55	2.07	1.00	0.91	1.94
1952	0.98	0.91	1.05	1.48	2.19	3.59	3.62	3.30	2.17	1.05	1.09	0.92	1.86
1953	0.98	0.88	1.18	1.39	2.17	3.39	3.35	2.88	2.12	1.72	1.07	0.85	1.83
1954	0.86	0.99	0.90	1.86	1.83	3.12	3.76	3.99	2.61	2.12	1.22	0.97	2.02
1955	0.81	0.89	1.06	1.70	2.38	2.74	4.16	3.32	2.55	1.63	1.01	0.92	1.93
1956	0.93	1.05	0.96	1.25	2.55	3.04	3.53	3.43	2.20	1.76	1.16	1.15	1.92
No.	10	11	11	11	11	11	11	11	11	11	11	11	10
Mean	0.92	0.94	1.09	1.57	2.22	3.23	3.61	3.43	2.47	1.83	1.14	0.96	1.95
Std Dev σ	0.15	0.16	0.19	0.22	0.21	0.31	0.41	0.34	0.24	0.36	0.16	0.10	0.08
C.V.(%)	16	17	18	14	9	9	11	10	10	20	14	10	4

Caribou : 14607 Sfc. Press. 991 mb; Elev. 191 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946	0.44	0.44	0.74	0.84	1.44	1.95	2.47	2.45	1.88	1.48	0.87	0.49	1.29
1947	0.42	0.56	0.57	0.66	1.47	2.07	3.19	2.66	1.90	1.52	0.90	0.48	1.37
1948	0.37	0.30	0.48	0.84	1.41	1.75	2.40	2.61	1.79	1.21	1.09	0.58	1.24
1949	0.52	0.48	0.64	0.94	1.39	2.36	2.59	2.48	1.91	1.40	0.83	0.65	1.35
1950	0.57	0.42	0.50		1.25	2.15		2.37	1.51		1.12	0.70	
1951		0.68	0.68		1.37	1.86		2.43	1.86		0.84	0.54	
1952		0.58	0.63		1.46	2.10		2.35	1.92		0.89	0.63	
1953		0.53	0.76		1.43	1.97		2.25	1.95		1.06	0.69	
1954	0.42	0.69	0.54	0.78	1.56	2.03	2.43	2.10	1.78	1.43	0.88	0.65	1.27
1955	0.57	0.53	0.58	0.94	1.57	2.16	2.46	2.57	1.74	1.30	0.83	0.43	1.31
1956	0.88	0.46	0.42	0.91	1.01	2.14	2.22	2.02	1.67	1.34	0.91	0.60	1.22
No.	8	11	11	7	11	11	7	11	11	7	11	11	7
Mean	0.52	0.52	0.60	0.84	1.40	2.05	2.54	2.39	1.81	1.38	0.93	0.59	1.30
Std Dev σ		0.12	0.14		0.16	0.17		0.20	0.13		0.11	0.09	
C.V.(%)		23	23		11	8		8	7		12	16	

Dodge City : 13985 Sfc. Press. 924 mb; Elev. 792 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946	0.70	0.68	1.07	1.49	1.65	2.40	2.75	3.15	2.44	1.67	1.17	0.88	1.67
1947	0.67	0.68	0.91	1.32	1.98	2.49	2.85	3.11	2.18	1.88	0.99	0.79	1.65
1948	0.78	0.90	0.86	1.19	1.78	2.88	3.13	3.00	2.12	1.19	0.89	0.75	1.62
1949	0.78	0.73	1.05	1.36	2.13	3.08	3.64	3.04	2.39	1.65	1.05	0.66	1.80
1950	0.70	0.84	0.75	1.15	1.71	2.64	3.25	2.97	2.34	1.63	0.69	0.84	1.64
1951	0.68	0.91	0.77	1.10	2.00	2.69	3.44	3.35	2.05	1.59	0.95	0.73	1.69
1952	0.72	0.76	0.85	1.29	1.84	2.85	2.60	3.26	1.87	0.99	0.90	0.70	1.57
1953	0.83	0.69	0.96	1.20	1.79	2.62	3.44	3.00	2.02	1.53	1.06	0.73	1.66
1954	0.77	0.85	0.76	1.33	1.89	2.35	2.97	3.13	2.16	1.66	0.94	0.69	1.62
1955	0.68	0.63	0.67	1.04	1.88	2.25	3.14	3.06	2.24	1.30	0.72	0.79	1.53
1956	0.80	0.67	0.69	0.98	2.02	2.67	2.97	2.68	1.83	1.43	0.83	0.73	1.52
No.	11	11	11	11	11	11	11	11	11	11	11	11	11
Mean	0.74	0.76	0.85	1.22	1.88	2.63	3.13	3.07	2.15	1.50	0.95	0.75	1.64
Std Dev σ	0.06	0.11	0.14	0.15	0.15	0.25	0.30	0.18	0.20	0.25	0.12	0.06	0.07
C.V.(%)	8	14	16	12	8	9	10	6	9	17	12	8	5

below −40° C., relative humidity data are not obtained from radiosondes. When the mean monthly temperature for a layer was below −40° C. and no mean relative humidity was given, the precipitable water was assumed to be zero. Missing relative humidities at 350 mb. were corrected using the "motorboating" value for the appropriate temperature. This was done only at 350 mb. and only when such a correction would complete the computation for a month.

TABLE 2.—Continued.

El Paso : 23044 Sfc. Press. 881 mb; Elev. 1195 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946	0.85		0.83	1.13	1.02	1.82	2.51	2.71	2.75	1.60	0.88	0.94	
1947	0.81	0.67	0.90	0.77	1.33	1.58	2.25	2.93	1.71	1.25	0.89	0.71	1.32
1948	0.73	0.88	0.72	0.85	1.23	2.11	2.66	2.54	2.13	1.66	0.66	1.05	1.44
1949	0.90	0.75	0.76	1.08	1.30	2.06	3.04	2.92	2.72	1.56	0.89	0.89	1.57
1950	0.92	0.88	0.76	0.88	0.97	2.00	3.17	2.33	2.17	1.74	0.83	0.76	1.45
1951	0.69	0.90	0.86	0.97	1.15	1.28	2.88	3.04	1.91	1.60	1.06	0.86	1.43
1952	1.02	0.67	0.70	1.19	1.31	2.34	2.90	2.82	1.81	0.99	0.99	0.76	1.46
1953	0.68	0.58	0.91	0.81	0.94	1.64	2.88	2.38	1.30	1.20	0.80	0.58	1.22
1954	0.72	0.69	0.77	0.95	1.33	1.62	2.66	2.96	2.45	1.64	0.77	0.66	1.43
1955	0.73	0.51	0.83	0.66	1.22	1.52	2.92	2.93	2.11	1.51	0.82	0.93	1.39
1956	0.85	0.72	0.60	0.83	1.02	2.22	2.61	2.42	1.60	1.29	0.62	0.77	1.30
No.	11	10	11	11	11	11	11	11	11	11	11	11	10
Mean	0.81	0.73	0.79	0.92	1.17	1.84	2.77	2.73	2.06	1.46	0.84	0.81	1.41
Std Dev σ	0.11	0.13	0.10	0.16	0.16	0.34	0.26	0.27	0.46	0.24	0.13	0.14	0.10
C.V. (%)	14	18	12	18	13	18	10	10	22	16	16	17	8

Fort Worth : 13911 Sfc. Press. 995 mb; Elev. 178 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946	1.37	1.31	1.72	2.18	2.79	3.39	3.40	3.76	3.72	2.51	1.75	1.53	2.45
1947	1.31	0.98	1.38	2.30	2.59	3.22	3.40	3.87	3.02	2.65	1.51	1.38	2.30
1948	1.13	1.60	1.44	2.23	2.84	3.39	4.11	3.79	2.78	1.96	2.05	1.83	2.43
1949	1.62	1.43	1.82		3.29	4.15							
1950				2.13	3.11	3.68	4.34		3.43				
1951				1.55			4.00	4.39		2.54	1.77		
1952		1.54	1.59		2.89		4.26	3.57			1.71		
1953	1.19	1.22	1.87	1.94	2.73	3.70	4.46	4.46	2.77	2.59	1.65	1.25	2.49
1954	1.50	1.20	1.26	2.69	2.98	3.51	4.08	3.91	3.02	2.72	1.49	1.32	2.47
1955	1.30	1.21	1.65	2.10	2.99	3.42	4.27	4.21	3.69	2.05	1.34	1.19	2.45
1956	1.30	1.41	1.26	1.87	3.04	3.75	3.72	3.26	2.51	2.46	1.33	1.47	2.28
No.	8	9	9	9	10	9	10	9	8	8	9	7	7
Mean	1.34	1.32	1.55	2.11	2.93	3.58	4.00	3.91	3.12	2.44	1.62	1.42	2.45
Std Dev σ		0.20	0.23	0.31	0.20	0.27	0.38	0.39			0.23		
C.V. (%)		15	15	15	7	8	9	10			14		

Ely : 23154 Sfc. Press. 808 mb; Elev. 1908 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946	0.47	0.49	0.62	0.88	0.97	0.98	1.63	1.56	1.04	0.85	0.68	0.67	0.90
1947	0.43	0.67	0.69	0.84	1.20	1.32	1.14	1.37	1.19	1.08	0.61	0.57	0.93
1948	0.55	0.51	0.47	0.69	0.84	1.20	1.12	1.12	1.03	0.77	0.59	0.50	0.78
1949	0.35	0.41	0.63	0.70	1.08	1.17	1.32	1.26	1.07	0.96	0.81	0.53	0.86
1950	0.43	0.56	0.57	0.66	0.85	0.88	1.76	1.15	1.35	0.85	0.78	0.72	0.88
1951	0.52	0.53	0.52	0.88	1.00	1.14	1.71	1.44	0.87	0.77	0.70	0.54	0.88
1952	0.49	0.44	0.54	0.83	0.94	0.98	1.65	1.48	1.10	0.57	0.50	0.63	0.85
1953	0.69	0.50	0.50	0.61	0.69	0.86	1.72	1.11	0.99	0.87	0.76	0.51	0.82
1954	0.57	0.58	0.50	0.71	0.91	1.04	1.53	1.04	1.02	0.85	0.78	0.51	0.84
1955	0.48	0.46	0.50	0.56	0.84	1.16	1.47	1.93	1.09	0.91	0.68	0.73	0.90
1956	0.61	0.41	0.50	0.75	1.06	1.00	1.35	0.95	1.02	0.94	0.56	0.59	0.81
No.	11	11	11	11	11	11	11	11	11	11	11	11	11
Mean	0.51	0.51	0.55	0.74	0.94	1.07	1.49	1.31	1.07	0.86	0.68	0.59	0.86
Std Dev σ	0.10	0.08	0.07	0.11	0.14	0.15	0.23	0.29	0.12	0.13	0.11	0.08	0.04
C.V. (%)	19	16	13	15	15	14	15	22	11	15	16	14	5

Grand Junction : 23066 Sfc. Press. 852 mb; Elev. 1474 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946	0.56	0.55	0.76	1.09	1.17	1.17	1.96	2.22	1.19	1.08	0.84	0.80	1.12
1947	0.51	0.70	0.77	0.89	1.35	1.61	1.94	2.44	1.57	1.44	0.74	0.68	1.22
1948	0.62	0.63	0.70	0.95	1.07	1.58	1.81	2.00	1.50	1.01	0.75	0.65	1.11
1949	0.58	0.54	0.88	1.06	1.41	1.74	2.28	1.90	1.64	1.21	0.90	0.65	1.23
1950	0.62	0.75	0.66	0.86	0.95	1.05	2.07	1.55	1.67	0.96	0.76	0.79	1.06
1951	0.61	0.65	0.57	0.90	1.22	1.26	1.79	1.98	1.12	1.06	0.68	0.63	1.04
1952	0.61	0.60	0.66	0.99	1.21	1.36	1.89	2.30	1.38	0.69	0.68	0.69	1.09
1953	0.80	0.57	0.74	0.78	0.99	1.16	2.19	1.98	1.23	1.13	0.94	0.55	1.09
1954	0.67	0.64	0.60	0.79	1.22	1.21	2.47	1.68	1.84	1.18	0.88	0.61	1.15
1955	0.60	0.48	0.59	0.69	1.07	1.32	1.82	2.59	1.27	0.91	0.76	0.77	1.07
1956	0.75	0.50	0.49	0.89	1.11	1.14	1.80	1.66	1.12	0.98	0.63	0.61	0.97
No.	11	11	11	11	11	11	11	11	11	11	11	11	11
Mean	0.63	0.60	0.68	0.90	1.16	1.33	2.00	2.03	1.41	1.06	0.78	0.68	1.10
Std Dev σ	0.08	0.08	0.11	0.12	0.14	0.22	0.22	0.33	0.25	0.19	0.11	0.09	0.07
C.V. (%)	13	14	16	14	12	17	11	17	17	18	14	13	7

Fairbanks : 26411 Sfc. Press. 993 mb; Elev. 135 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946													
1947		0.67	0.57	0.57	1.13	1.58	2.21	1.66	1.22	0.82	0.67	0.50	
1948	0.44	0.32	0.35	0.60	1.10	1.88	2.12	1.63	1.30	0.84	0.37	0.28	0.94
1949	0.37	0.32	0.62	0.55	0.98	1.50	2.18	1.99	1.53	0.85	0.66	0.34	0.99
1950	0.46	0.18	0.52	0.49	1.00	1.53	2.04	1.97	1.36	0.78	0.37	0.41	0.93
1951	0.24	0.33	0.27	0.71	1.03	1.51	2.08	2.08	1.42	0.65	0.67	0.37	0.95
1952	0.25	0.41	0.41	0.52	0.79	1.64	2.07	1.74	1.28	0.91	0.69	0.41	0.93
1953	0.20	0.37	0.35	0.68	1.18	1.94	2.01	1.82	1.28	0.68	0.48	0.42	0.95
1954	0.28	0.21	0.41	0.43	0.92	1.65	1.96	1.97	1.26	0.84	0.60	0.28	0.90
1955	0.47	0.28	0.44	0.46	1.00	1.52	1.97	1.69	1.31	0.72	0.34	0.31	0.88
1956	0.28	0.30	0.34	0.59	1.04	1.56	2.06	1.99	1.12	0.56	0.39	0.23	0.87
No.	9	10	10	10	10	10	10	10	10	10	10	10	9
Mean	0.33	0.34	0.43	0.56	1.02	1.63	2.07	1.85	1.31	0.77	0.52	0.36	0.93
Std Dev σ	0.11	0.13	0.11	0.09	0.11	0.16	0.08	0.17	0.11	0.11	0.15	0.08	0.04
C.V. (%)	33	40	26	16	11	10	4	9	8	14	28	23	4

Great Falls : 24143 Sfc. Press. 886 mb; Elev. 1123 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946	0.56	0.57	0.72	0.88	1.14	1.56	1.91	1.57	1.44	0.86	0.71	0.62	1.05
1947	0.46	0.50	0.70	0.86	1.15	1.52	1.71	1.78	1.50	1.17	0.70	0.66	1.06
1948	0.55	0.47	0.53	0.79	1.31	1.99	1.82	1.82	1.29	0.88	0.63	0.42	1.04
1949	0.36	0.40	0.58	0.83	1.29	1.41	1.72	1.72	1.32	0.92	0.83	0.47	0.99
1950	0.25	0.36	0.34	0.74	0.96	1.53	1.85	1.81	1.31	1.11	0.61	0.76	1.00
1951	0.42	0.52	0.50	0.72	1.09	1.36	1.84	1.87	1.30	1.04	0.71	0.46	0.99
1952	0.44	0.53	0.55	0.88	1.32	1.61	1.61	1.82	1.48	0.99	0.73	0.64	1.05
1953	0.72	0.61	0.68	0.78	1.05	1.63	1.73	1.79	1.30	1.08	0.79	0.65	1.07
1954	0.46	0.66	0.54	0.75	1.14	1.47	1.90	1.98	1.50	1.00	0.97	0.38	1.08
1955	0.55	0.48	0.42	0.80	1.16	1.61	2.14	1.50	1.40	1.10	0.55	0.58	1.02
1956	0.58	0.45	0.56	0.86	1.37	1.65	1.92	1.79	1.42	1.01	0.68	0.67	1.08
No.	11	11	11	11	11	11	11	11	11	11	11	11	11
Mean	0.49	0.52	0.58	0.81	1.18	1.58	1.83	1.77	1.39	1.02	0.72	0.59	1.04
Std Dev σ	0.13	0.07	0.09	0.06	0.13	0.17	0.14	0.14	0.09	0.09	0.12	0.10	0.01
C.V. (%)	26	14	15	8	11	11	8	8	7	9	16	18	1

A major adjustment of the data was made. The relative humidity values for the period of record, 1946–56, are not homogeneous. Prior to October 1948 relative humidity at temperatures below 0° C. was expressed with respect to ice saturation and after that date with respect to water. Thus there exists a real difference in the two periods of record, and differences in computed values of precipitable water of about 10 percent could result for

TABLE 2.—Continued.

Greensboro : 13723 Sfc. Press. 986 mb; Elev. 273 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946	1.20	0.97	1.56	1.69	2.51	2.98	3.75	3.46	2.92	1.92	1.76	1.28	2.17
1947	1.62	0.61	0.90	1.85	2.25	3.02	3.16	4.03	3.28	2.53	1.42	0.87	2.13
1948	0.89	1.46	1.47	1.99	2.39	3.28	3.91	3.63	2.99	1.59	1.99	1.43	2.25
1949	1.77	1.43	1.20	1.50	2.51	3.63	4.57	4.16	2.79	2.65	1.27	1.25	2.39
1950	1.83	1.22	1.13	1.32	2.86	3.18	3.86	3.42	3.08	2.25	1.10	0.88	2.18
1951	1.02	1.09	1.30	1.55	2.21	3.41	3.87	3.85	2.94	2.06	1.30	1.13	2.14
1952	1.33	1.16	1.26	1.74	2.32	3.56	3.67	3.90	2.64	1.46	1.41	1.01	2.12
1953	1.29	1.22	1.33	1.48	2.66	3.38	3.48	3.35	2.71	1.77	1.20	1.09	2.08
1954	1.06	1.04	1.18	2.19	2.13	2.97	3.53	3.68	2.57	2.00	1.34	0.95	2.05
1955	1.01	1.03	1.30	1.81	2.40	2.60	4.15	3.93	3.25	1.84	1.15	0.83	2.11
1956	0.90	1.29	1.10	1.38	2.59	3.22	3.91	3.55	3.03	2.46	1.25	1.51	2.18
No.	11	11	11	11	11	11	11	11	11	11	11	11	11
Mean	1.27	1.14	1.25	1.68	2.44	3.20	3.81	3.72	2.93	2.05	1.38	1.11	2.16
Std Dev σ	0.34	0.24	0.18	0.27	0.22	0.30	0.37	0.26	0.24	0.39	0.27	0.23	0.10
C.V. (%)	27	21	15	16	9	9	10	7	8	19	19	21	5

Havana : 12864 Sfc. Press. 1010 mb; Elev. 49 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946	3.14		3.02		4.28	4.62	4.40	4.39	4.68	3.94	3.81	3.53	
1947	3.27		2.78	3.57	3.80	4.52	4.63	4.56	4.90	4.65	4.01	3.17	
1948	2.75	2.79		3.35									
1949													
1950		2.85	3.16	2.80	3.54	3.95	4.30	4.48	4.78	4.62	2.93	2.51	
1951	2.35	2.31	2.84	3.54	3.42	4.02	4.83	4.91	4.80	4.47	3.41	3.18	3.67
1952	2.43	2.58	3.18	3.00	4.37	4.31	3.86	4.57	4.79	4.66	3.36	2.65	3.65
1953	2.68	2.72					4.52	4.67	4.88	4.13	3.63	3.14	
1954													
1955													
1956													
No.	6	5	5	5	5	5	6	6	6	6	6	6	2
Mean	2.77	2.65	3.00	3.25	3.88	4.28	4.42	4.59	4.81	4.41	3.53	3.03	3.72
Std Dev σ													
C.V. (%)													

Guantanamo Bay : 11706 Sfc. Press. 1013 mb; Elev. 25 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946													
1947													
1948								4.01	4.58	4.60	3.99		
1949						4.58	4.13	4.57		4.94	4.66	4.24	
1950					4.44	4.64		4.76	4.89	4.86	4.44	4.30	
1951	3.02	2.96		3.72	4.71	4.41	4.77	5.02	4.80	4.47	4.24	3.37	
1952	2.58	3.09	3.26	3.89	4.48	4.48	4.15	4.45	4.86	4.82	3.62	3.20	3.91
1953	3.35	3.04	3.06	3.86	4.25	4.75	4.28	4.42	4.71	4.70	4.07	3.37	3.99
1954	3.11	3.67	3.26	3.43	4.40	4.31	4.20	4.34	4.42	4.37	4.04	3.13	3.89
1955	2.78	3.14	2.80	3.19	3.98	4.60	4.29	4.62	4.85	4.69	3.63	3.78	3.86
1956	2.54	3.00	3.51	3.45	4.17	4.23	3.82	4.11	4.24	4.53	4.01	3.37	3.75
No.	6	6	5	6	7	8	7	9	8	9	9	8	
Mean	2.90	3.15	3.18	3.59	4.35	4.50	4.23	4.48	4.67	4.66	4.08	3.60	3.95
Std Dev σ								0.31		0.20	0.34		
C.V. (%)								7		4	8		

International Falls : 14918 Sfc. Press. 1016 mb; Elev. 5 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946	0.48	0.39	0.85	0.97	1.34	1.99	2.38	2.21	1.75	1.25	0.77	0.41	1.23
1947	0.43	0.35	0.47	0.72	1.09	1.90	2.59	2.78	1.91	1.69	0.60	0.52	1.25
1948	0.33	0.38	0.53	1.03	1.25	2.03	2.68	2.58	1.78	1.15	0.81	0.53	1.26
1949	0.51	0.38	0.51	0.99	1.54	2.27	2.78	2.62	1.65	1.27	0.86	0.44	1.32
1950	0.33	0.45	0.43	0.77	1.35	1.96	2.50	2.04	1.91	1.60	0.65	0.49	1.21
1951	0.37	0.54	0.57	0.96	1.66	1.97	2.47	2.54	1.75	1.25	0.55	0.37	1.25
1952	0.43	0.48	0.51	0.93	1.28	2.37	2.49	2.25	1.80	0.89	0.70	0.64	1.23
1953	0.54	0.43	0.66	0.75	1.39	2.33	2.20	2.62	1.72	1.36	0.84	0.47	1.28
1954	0.37	0.66	0.40	0.79	1.24	2.15	2.66	2.28	1.75	1.13	0.90	0.57	1.24
1955	0.41	0.41	0.41	1.19	1.64	2.36	2.98	2.42	1.75	1.28	0.69	0.43	1.33
1956	0.57	0.37	0.45	0.70	1.15	2.24	2.28	2.24	1.46	1.38	0.77	0.56	1.18
No.	11	11	11	11	11	11	11	11	11	11	11	11	11
Mean	0.43	0.44	0.53	0.89	1.36	2.14	2.55	2.42	1.75	1.30	0.74	0.49	1.25
Std Dev σ	0.08	0.09	0.13	0.15	0.19	0.17	0.23	0.23	0.13	0.22	0.11	0.08	0.03
C.V. (%)	19	21	25	17	14	8	9	10	7	17	15	16	3

Hatteras : 13745 Sfc. Press. 1017 mb; Elev. 3 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946					3.13		4.03	4.01	3.56				
1947	1.90						3.83	4.40	3.89	2.90	1.85	1.45	
1948	1.31	1.87	1.84	2.19	2.74	3.69	4.27	3.63	3.43	2.15	2.54	1.79	2.62
1949	2.08	1.70	1.45	1.95	2.64	4.00	4.36	4.53	3.51	3.07	1.54	1.61	2.70
1950	2.24	1.42	1.48	1.69	2.86	3.48	4.51	3.73	3.62	2.70	1.57	1.29	2.55
1951	1.38	1.41	1.45	1.80	2.43	3.61	4.00	4.22	3.66	2.87	1.76	1.50	2.51
1952	1.50	1.37	1.48	1.94	2.57	3.59	4.04	4.12	3.49	1.90	1.73	1.31	2.42
1953	1.53	1.55	1.63	1.83	2.95	3.18	4.00	3.80	3.10	2.44	1.63	1.62	2.44
1954	1.33	1.20	1.33	2.23	2.44	3.50	3.93	3.97	3.19	2.28	1.70	1.12	2.35
1955	1.21	1.35	1.82	2.10	2.50	2.90	4.13	4.30	3.97	2.07	1.50	1.18	2.42
1956	1.21	1.76	1.38	1.65	2.74	3.84	4.06	3.87	3.15	3.00	1.65	1.59	2.49
No.	10	9	9	9	10	9	11	11	11	10	10	10	9
Mean	1.57	1.52	1.56	1.93	2.70	3.53	4.11	4.05	3.51	2.54	1.75	1.45	2.52
Std Dev σ	0.37	0.22	0.18	0.21	0.23	0.33	0.21	0.28	0.29	0.42	0.30	0.22	0.12
C.V. (%)	24	15	12	11	9	9	5	7	8	17	17	15	5

Lake Charles : 13941 Sfc. Press. 1016 mb, Elev. 5 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946					3.34		4.58	4.34	4.23		2.86		
1947	2.20				3.10		3.72	4.55	3.53		2.27	2.05	
1948	1.72	2.36	2.47	2.57	3.20	3.70	4.72	4.29	3.69	2.24	2.41	2.12	2.96
1949	2.27	2.40	2.11	2.56	3.03	4.03	4.82	4.28	4.29	3.80	1.58	2.26	3.12
1950	2.88	2.20	1.83	2.57	3.36	4.16	4.53	4.16	3.99	2.95	1.82	1.82	3.02
1951	1.92	1.90	2.10	2.11	2.95	4.03	4.96	4.72	4.36	2.84	2.00	2.22	3.01
1952	2.35	1.84	1.78	2.15	3.04	3.80	4.67	4.45	3.37	1.48	2.12	1.85	2.74
1953	1.55	2.08	2.63	2.43	3.50	4.05	4.33	4.62	3.07	2.45	1.97	1.74	2.87
1954	1.90	1.52	1.82	2.74	2.86	3.75	4.48	4.14	3.94	2.96	1.84	1.72	2.81
1955	1.79	2.03	2.11	2.52	3.24	3.40	4.73	4.67	4.60	2.39	2.26	1.97	2.98
1956	1.65	2.13	2.04	2.40	3.38	3.95	4.17	4.22	3.43	2.80	1.94	2.13	2.85
No.	10	9	9	9	11	9	11	11	11	9	11	10	9
Mean	2.02	2.05	2.10	2.45	3.18	3.87	4.52	4.40	3.86	2.66	2.10	1.99	2.93
Std Dev σ	0.40	0.27	0.29	0.21	0.20	0.22	0.35	0.20	0.48	0.63	0.35	0.20	0.13
C.V. (%)	20	13	14	8	6	6	8	5	12	24	17	10	4

stations at high elevations during the cold months. Thus the relative humidity data for the period from January 1946 through September 1948 were adjusted so that they were expressed in terms of saturation over water.

3. VALUES OF MEAN MONTHLY PRECIPITABLE WATER

Table 1 lists the 52 stations and the number of months for which mean monthly values were determined.

TABLE 2.—Continued.

Lander : 24021 Sfc. Press. 828 mb; Elev. 1696 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946	0.48	0.47	0.65	0.89	1.12	1.32	1.84	1.56	1.30	0.89	0.62	0.58	0.98
1947	0.41	0.45	0.60	0.80	1.25	1.29	1.72	1.60	1.31	1.07	0.60	0.53	0.97
1948	0.46	0.44	0.46	0.65	0.98	1.64	1.49	1.51	1.30	0.85	0.53	0.41	0.89
1949	0.35	0.33	0.60	0.80	1.26	1.47	1.60	1.53	1.29	0.91	0.75	0.43	0.94
1950	0.31	0.47	0.49	0.70	0.91	1.27	1.68	1.49	1.43	0.97	0.68	0.59	0.92
1951	0.36	0.47	0.47	0.74	1.13	1.25	1.88	1.66	1.22	0.89	0.53	0.45	0.92
1952	0.41	0.47	0.50	0.88	1.17	1.33	1.61	1.75	1.24	0.88	0.56	0.47	0.94
1953	0.62	0.50	0.55	0.66	0.97	1.21	1.77	1.73	1.18	1.03	0.69	0.48	0.95
1954	0.51	0.56	0.50	0.60	1.16	1.07	1.63	1.16	1.13	0.82	0.73	0.43	0.86
1955	0.40	0.40	0.37	0.61	0.83	1.36	1.41	1.80	1.20	0.81	0.54	0.55	0.86
1956	0.47	0.33	0.44	0.76	1.13	1.09	1.56	1.42	0.97	0.84	0.53	0.49	0.84
No.	11	11	11	11	11	11	11	11	11	11	11	11	11
Mean	0.44	0.45	0.51	0.74	1.08	1.30	1.65	1.57	1.23	0.91	0.62	0.49	0.92
Std Dev σ	0.08	0.07	0.08	0.10	0.14	0.16	0.14	0.17	0.11	0.09	0.08	0.06	0.05
C.V. (%)	19	15	16	14	13	12	8	11	9	10	13	12	6

Mazatlan : 22009 Sfc. Press. 1010 mb; Elev. 14 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946													
1947													
1948													
1949													
1950	1.92	2.00	1.86	1.94	2.84	4.77	5.11	5.21	5.36	4.51	3.05	2.32	3.41
1951	1.99	1.79	2.33	2.26	2.68	4.21	5.50	5.52	5.13	4.49	3.70	3.36	3.58
1952	2.37	2.05	2.06		2.42	5.24	5.48	5.58	5.36	3.98	3.36	2.76	
1953	1.77	2.11	2.40	2.07	2.74	4.85	5.54	5.57	4.63	4.60	2.52	2.18	3.41
1954	2.48	2.45	1.80	1.72	2.73	4.97	5.27	5.37	5.33	4.59	2.64	2.73	3.51
1955	2.87	2.21	2.23	2.00	3.07	4.75	3.68	5.88	5.77	4.79	3.49	2.43	3.76
1956	2.38	1.87	1.70	2.13	3.99	5.24	5.10	5.28	4.94	4.40	3.50	2.65	3.60
No.	7	7	7	6	7	7	7	7	7	7	7	7	6
Mean	2.25	2.07	2.05	2.02	2.92	4.86	5.38	5.49	5.22	4.48	3.18	2.63	3.55
Std Dev σ													
C.V. (%)													

Las Vegas : 23169 Sfc. Press. 939 mb; Elev. 600 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946	0.71	0.67	0.96	1.15	1.24	1.07	2.47	2.45	1.59	1.32	1.14	1.12	1.32
1947	0.64	0.97	1.01	1.14	1.46	1.42	1.61	2.34	1.75	1.55	1.00	0.93	1.32
1948	0.74	0.79	0.71	1.03	0.95	1.45	1.66	1.80	1.59	1.35	0.81	0.76	1.14
1949	0.67	0.77	0.89	1.14	1.38	1.87	2.08	1.64	1.51	1.24	1.04	0.76	1.27
1950	0.74	0.91	0.76	0.83	0.96	1.08	2.54	1.75	1.62	1.09	1.07	0.99	1.20
1951	0.87	0.82	0.70	1.07	1.24	1.22	2.36	2.36	1.27	1.12	0.96	0.87	1.24
1952	0.78	0.68	0.87	1.30	1.17	1.31	2.19	2.28	1.91	0.99	0.95	0.99	1.28
1953	1.04	0.61	0.72	0.88	0.83	1.15	2.90	1.92	1.34	1.15	1.02	0.60	1.18
1954	0.89	0.86	0.86	1.05	1.29	1.48	2.58	1.65	1.65	1.21	1.09	0.82	1.29
1955	0.82	0.67	0.73	0.74	1.13	1.38	2.25	3.33	1.45	1.30	1.06	1.10	1.33
1956	1.03	0.61	0.59	1.02	1.03	1.11	2.22	1.37	1.66	1.15	0.62	0.63	1.09
No.	11	11	11	11	11	11	11	11	11	11	11	11	11
Mean	0.81	0.76	0.80	1.03	1.15	1.32	2.26	2.10	1.58	1.23	0.98	0.87	1.24
Std Dev σ	0.13	0.12	0.13	0.16	0.19	0.24	0.38	0.53	0.18	0.15	0.15	0.17	0.07
C.V. (%)	16	16	16	16	17	18	17	25	12	12	15	20	6

Medford : 24225 Sfc. Press. 1017 mb; Elev. 4 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946	1.14	1.09	1.30	1.44	1.63	1.89	2.32	2.12	1.88	1.52	1.35	1.26	1.58
1947	1.03	1.36	1.32	1.49	1.84	1.86	2.37	2.08	1.92	1.98	1.42	1.24	1.66
1948	1.08	0.99	1.13	1.21	1.59	2.34	2.22	2.17	1.89	1.57	1.25	0.90	1.53
1949	0.67	0.99	1.15	1.44	1.77	1.81	2.10	2.14	2.11	1.46	1.56	1.07	1.52
1950	0.88	1.14	1.10	1.28	1.49	2.06	1.88	2.20	1.99	1.97	1.68	1.55	1.60
1951	1.09	1.21	0.98	1.41	1.61	1.67	2.07	1.96	1.88	1.71	1.40	1.08	1.51
1952	1.00	1.14	1.02	1.38	1.63	2.05	2.32	2.28	2.13	1.80	1.01	1.20	1.58
1953	1.34	1.20	1.12	1.21	1.51	1.73	1.92	2.51	2.16	1.68	1.60	1.33	1.61
1954	1.19	1.21	1.05	1.28	1.69	1.86	2.06	2.12	1.81	1.48	1.57	1.19	1.54
1955	1.01	0.95	1.03	1.12	1.45	2.03	2.04	1.79	1.76	1.92	1.40	1.26	1.48
1956	1.17	0.92	1.09	1.40	1.82	1.91	2.45	2.28	1.91	1.66	1.29	1.19	1.59
No.	11	11	11	11	11	11	11	11	11	11	11	11	11
Mean	1.06	1.11	1.12	1.33	1.64	1.93	2.16	2.15	1.95	1.71	1.41	1.21	1.56
Std Dev σ	0.17	0.14	0.11	0.12	0.13	0.19	0.19	0.18	0.13	0.19	0.19	0.17	0.03
C.V. (%)	16	12	10	11	8	10	9	9	7	11	13	14	2

Little Rock : 13963 Sfc. Press. 1007 mb; Elev. 79 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946	1.31	1.30	1.78	2.34	2.89	3.48	4.06	3.95	3.23	2.26	2.10	1.69	2.53
1947	1.53	0.88	1.26	2.31	2.93	3.81	3.54	4.39	3.28	2.77	1.64	1.26	2.47
1948	1.11	1.60	1.65	2.36	2.91	3.76	4.58	4.21	3.12	2.06	1.78	1.59	2.56
1949	1.98	1.39	1.64	1.99	2.93	4.07	4.85	4.26	3.20	2.99	1.47	1.46	2.69
1950	2.24	1.63	1.38	1.79	3.06	3.58	4.22	4.19	3.63	2.65	1.42	1.17	2.58
1951	1.33	1.40	1.67	1.99	2.45	3.93	4.52	4.58	3.42	2.31	1.56	1.54	2.56
1952	1.81	1.55	1.33	1.90	2.64	3.74	4.17	4.00	2.65	1.26	1.56	1.24	2.32
1953	1.47	1.20	1.81	1.78	2.97	3.92	4.15	3.92	2.51	2.01	1.31	1.13	2.35
1954	1.45	1.22	1.34	2.37	2.62	3.75	4.43	4.22	2.89	2.51	1.42	1.26	2.46
1955	1.15	1.29	1.62	2.09	2.80	3.19	4.59	4.03	3.29	2.02	1.36	1.19	2.39
1956	1.23	1.50	1.33	1.79	3.15	3.68	4.03	4.04	2.19	2.22	1.42	1.64	2.35
No.	11	11	11	11	11	11	11	11	11	11	11	11	11
Mean	1.51	1.36	1.53	2.06	2.85	3.72	4.29	4.16	3.04	2.28	1.55	1.38	2.48
Std Dev σ	0.36	0.22	0.20	0.25	0.21	0.24	0.36	0.19	0.14	0.34	0.23	0.17	0.12
C.V. (%)	24	16	13	12	7	7	9	5	5	15	15	12	5

Miami : 12839 Sfc. Press. 1017 mb; Elev. 4 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946					4.06	4.43	4.47	4.68	4.77		3.52		
1947				3.57	3.43	4.81	4.71	4.65	4.91	4.17	3.89		
1948	2.76				3.49		4.92	4.92	4.88	4.02	3.73	3.26	
1949	2.39	2.76	2.44	3.24	3.33	4.45	4.67	4.55	4.66	4.16	2.53	2.89	3.50
1950	2.61	2.48	2.74	2.36	3.40	3.98	4.25	4.67	4.57	4.21	2.54	2.39	3.35
1951	2.01	2.02	2.43	3.08	3.11	4.07	4.82	4.95	4.64	4.18	2.99	2.69	3.41
1952	2.33	2.15	2.77	2.35	3.54	4.09	4.35	4.64	4.38	4.57	2.94	2.23	3.36
1953	2.29	2.53	2.78	2.72	3.10	4.57	4.61	4.63	4.89	3.65	3.13	2.82	3.46
1954	2.42	2.10	2.57	3.49	3.70	4.43	4.44	4.49	4.68	3.50	2.48	1.91	3.35
1955	2.10	2.44	2.49	2.88	3.05	4.08	4.41	4.61	4.57	3.51	2.73	2.88	3.31
1956	1.87	2.67	2.19	2.53	3.37	3.68	4.13	4.43	4.48	3.60	2.52	2.32	3.15
No.	9	8	8	9	11	10	11	11	11	10	11	9	8
Mean	2.31	2.39	2.55	2.91	3.42	4.26	4.53	4.64	4.68	3.96	3.00	2.60	3.44
Std Dev σ	0.28			0.46	0.30	0.33	0.25	0.18	0.19	0.37	0.51	0.41	
C.V. (%)	12			16	9	8	6	4	4	9	17	16	

Twenty-nine stations had complete records and 44 stations had more than 108 complete months (9 years). Missing monthly values result from several considerations. Some stations do not have complete records because observations were not taken during all of the 11 years. Other missing monthly values result from errors in processing and computing, and the fact that the Institute's records were not complete. It does not seem necessary to complete the records for all stations.

TABLE 2.—Continued.

Midland : 23023 Sfc. Press. 924 mb; Elev. 871 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946	1.04	0.85	1.04	1.70		2.74	2.81	2.92	3.35	2.22	1.37	1.11	
1947	0.95	0.79	1.14	1.53	2.06	2.65	2.90	3.19	2.28	2.04	1.21	1.04	1.82
1948	0.86	1.13	1.00	1.40	2.12	2.74	3.38	2.98	2.28	1.74	0.93	1.13	1.81
1949	1.25	1.08	1.15	1.66	2.44	2.99	3.36	3.26	3.03	1.99	1.00	1.12	2.03
1950	1.20	1.17	0.86	1.46	2.11	2.97	3.47	2.97	2.99	1.90	0.90	0.73	1.89
1951	0.69	1.02	0.98	1.34	2.01	2.52	3.20	3.26	2.42	2.07	1.10	0.79	1.78
1952	1.18	0.78	0.86	1.40	1.81	2.79	3.32	3.12	2.41	1.13	1.22	0.84	1.74
1953	0.79	0.80	1.30	1.21	1.61	2.60	3.32	3.15	1.88	1.87	0.94	0.72	1.68
1954	0.89	0.78	0.81	1.62	1.99	2.74	2.60	3.41	2.25	1.96	1.04	0.89	1.75
1955	0.95	0.74	0.95	0.99	1.81	2.39	3.24	2.99	2.64	1.50	0.94	0.94	1.67
1956	0.93	0.84	0.75	1.15	2.00	2.75	2.75	2.53	2.02	1.66	0.78	0.93	1.59
No.	11	11	11	11	10	11	11	11	11	11	11	11	10
Mean	0.98	0.91	0.99	1.41	2.00	2.72	3.12	3.07	2.51	1.83	1.04	0.93	1.79
Std Dev σ	0.18	0.16	0.17	0.23	0.22	0.18	0.30	0.23	0.45	0.31	0.17	0.15	0.12
C.V. (%)	18	18	17	16	11	7	10	8	18	17	17	16	7

Nantucket, Mass. : 14756 Sfc. Press. 1015 mb; Elev. 14 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946				1.17		2.51	2.72	2.96	2.58	1.82	1.36	1.00	
1947	0.99	0.67	0.77	1.33	1.95	2.12	2.96	3.04	2.48	1.73	1.11	0.73	1.66
1948	0.73	0.75	1.17	1.33	2.13	2.63	2.91	3.27	2.20	1.77	1.73	1.00	1.80
1949	1.19	0.96	1.14	1.31	1.96	2.48	3.44	3.14	2.37	1.96	1.38	1.01	1.86
1950	1.33	0.93	0.87	1.29	1.86	2.53	3.08	2.84	2.37	1.75	1.54	1.07	1.79
1951	0.99	1.10	1.05	1.38	1.86	2.56	3.10	3.02	2.53	1.91	1.24	0.90	1.80
1952	1.02	0.78	0.99	1.53	1.71	2.74	2.93	3.16	2.27	1.53	1.23	0.90	1.73
1953	1.08	0.90	1.04	1.40	2.15	2.33	2.87	2.71	2.36	1.83	1.45	1.10	1.77
1954	0.91	0.96	0.89	1.45	1.94	2.50	2.97	2.86	2.58	2.17	1.42	1.06	1.81
1955	0.65	0.92	0.98	1.49	1.90	2.58	3.38	3.31	2.28	2.14	1.32	0.65	1.80
1956	1.00	0.91	0.90	1.18	1.55	2.73	3.02	2.93	2.37	1.68	1.39	1.25	1.74
No.	10	10	10	11	10	11	11	11	11	11	11	11	10
Mean	0.99	0.89	0.98	1.35	1.90	2.52	3.04	3.02	2.40	1.85	1.38	0.97	1.77
Std Dev σ	0.20	0.12	0.13	0.11	0.18	0.18	0.21	0.18	0.13	0.19	0.17	0.17	0.07
C.V. (%)	20	14	13	8	9	7	7	6	5	10	12	17	4

Nashville : 13897 Sfc. Press. 996 mb; Elev. 177 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946	1.05	1.13	1.78	2.02	2.56	3.34	4.08	3.35	3.08	1.90	1.76	1.50	2.30
1947	1.59	0.73	1.02	1.97	2.24	3.49	3.10	4.41	3.03	2.75	1.54	1.06	2.24
1948	0.89	1.49	1.62	2.11	2.37	3.40	3.96	3.40	2.71	1.63	1.74	1.27	2.22
1949	1.76	1.22	1.29	1.70	2.47	3.78	4.50	4.02	2.51	2.81	1.19	1.20	2.37
1950	2.04	1.28	1.18	1.45	2.87	3.21	3.63	3.57	3.15	2.28	1.21	0.90	2.23
1951	1.12	1.24	1.54	1.67	2.05	3.49	3.95	3.81	2.89	2.02	1.32	1.26	2.20
1952	1.50	1.15	1.06	1.59	2.29	3.55	3.51	3.73	2.38	1.23	1.16	1.13	2.02
1953	1.29	1.14	1.45	1.59	2.63	3.39							
1954	1.23	1.09	1.17	2.11	1.96	3.15	3.66	3.90	2.80	2.17	1.24	1.08	2.13
1955	0.96	1.18	1.41	1.87	2.52	2.53	4.28	4.05	2.86	1.73	1.21	1.05	2.14
1956	1.01	1.47	1.19	1.56	2.74	3.30	3.60	3.49	2.21	2.23	1.19	1.60	2.13
No.	11	11	11	11	11	11	10	10	10	10	10	10	10
Mean	1.31	1.19	1.34	1.79	2.43	3.33	3.83	3.77	2.76	2.08	1.36	1.21	2.20
Std Dev σ	0.37	0.20	0.24	0.24	0.28	0.32	0.41	0.33	0.31	0.49	0.23	0.21	0.09
C.V. (%)	28	17	18	14	12	10	11	9	11	23	17	18	4

North Platte : 24023 Sfc. Press. 916 mb; Elev. 848 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946	0.66	0.71	1.00	1.38	1.59	2.37	2.93	2.64	2.21	1.40	0.93	0.80	1.55
1947	0.59	0.60	0.76	1.15	1.73	2.40	2.80	3.09	2.23	1.85	0.80	0.78	1.57
1948	0.59	0.71	0.74	1.19	1.76	2.64	2.76	2.94	2.08	1.18	0.85	0.65	1.51
1949	0.60	0.56	0.93	1.18	2.00	2.63	2.88	2.83	1.80	1.45	0.99	0.64	1.54
1950	0.55	0.83	0.71	1.05	1.61	2.16	2.75	2.58	2.16	1.54	0.81	0.79	1.46
1951	0.58	0.77	0.63	0.95	1.77	2.27	2.90	3.08	1.84	1.39	0.76	0.67	1.47
1952	0.63	0.73	0.73	1.16	1.81	2.67	2.63	2.95	1.80	0.93	0.75	0.67	1.45
1953	0.86	0.68	0.84	1.01	1.54	2.41	2.84	2.83	1.80	1.41	1.07	0.68	1.50
1954	0.68	0.83	0.77	1.26	1.71	2.29	2.86	2.89	2.08	1.38	0.87	0.68	1.52
1955	0.59	0.57	0.67	1.02	1.65	2.20	2.86	2.62	1.95	1.22	0.67	0.76	1.41
1956	0.74	0.60	0.70	0.91	1.85	2.36	2.57	2.74	1.75	1.29	0.85	0.80	1.43
No.	11	11	11	11	11	11	11	11	11	11	11	11	11
Mean	0.64	0.69	0.77	1.11	1.73	2.40	2.80	2.85	1.97	1.37	0.85	0.72	1.49
Std Dev σ	0.09	0.10	0.11	0.15	0.13	0.18	0.12	0.15	0.18	0.23	0.11	0.07	0.06
C.V. (%)	14	14	14	13	8	7	4	5	9	17	13	9	4

Oakland : 23230 Sfc. Press. 1016 mb; Elev. 6 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946	1.08	1.21	1.51	1.45	1.74	1.71	2.24	1.67	1.76	1.65	1.53	1.52	1.59
1947	1.06	1.55	1.65	1.63	1.71	2.07	1.69	1.82	1.82	2.24	1.32	1.36	1.66
1948	1.45	1.29	1.39	1.56	1.79	2.16	1.96	1.74	1.88	1.84	1.53	1.37	1.66
1949	0.84	1.31	1.47	1.59	1.95	1.78	1.88	2.08	2.19	1.78	2.01	1.33	1.68
1950	1.32	1.49	1.41	1.50	1.52	1.92	1.88	1.93	2.24	2.20	2.13	1.90	1.79
1951	1.50	1.48	1.26	1.66	1.79	1.81	1.86	2.06	2.17	1.79	1.85	1.36	1.72
1952	1.29	1.48	1.33	1.55	1.54	1.85	2.30	1.80	2.15	1.87	1.28	1.61	1.67
1953	1.70	1.13	1.26	1.51	1.52	1.63	1.70	2.04	2.27	1.53	1.81	1.40	1.62
1954	1.40	1.35	1.34	1.70	1.50	1.89	2.00	1.86	1.64	1.62	1.82	1.44	1.63
1955	1.23	1.20	1.23	1.33	1.78	1.93	1.88	1.70	1.76	1.85	1.74	1.77	1.62
1956	1.61	1.15	1.25	1.51	1.87	1.81	2.13	1.90	2.05	1.96	1.35	1.30	1.66
No.	11	11	11	11	11	11	11	11	11	11	11	11	11
Mean	1.32	1.33	1.37	1.55	1.70	1.87	1.96	1.87	1.99	1.85	1.67	1.49	1.66
Std Dev σ	0.26	0.15	0.13	0.10	0.16	0.15	0.20	0.14	0.22	0.22	0.29	[illegible]	0.04
C.V. (%)	20	11	9	6	9	8	10	8	11	12	17	13	2

Oklahoma City : 13967 Sfc. Press. 970 mb; Elev. 392 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946	1.04	0.98	1.51	1.96	2.22	3.13	3.22	3.50	3.02	2.22	1.56	1.39	2.15
1947	1.00	0.77	1.15	1.86	2.31	3.20	3.48	3.76	2.80	2.55	1.30	1.13	2.11
1948	0.93	1.31	1.25	1.89	2.59	3.41	4.10	3.97	2.39	1.55	1.27	1.07	2.14
1949	1.26	1.10	1.24	1.68	2.80	3.52	4.06	3.24	2.88	2.10	1.20	1.09	2.18
1950	1.17	1.25	0.99	1.62	2.56	3.25	4.02	3.44	3.05	1.96	1.12	0.99	2.12
1951	0.86	1.24	1.05	1.55	2.53	3.40	3.82	3.99	2.94	2.31	1.24	0.93	2.16
1952	1.14	1.08	1.13	1.51	2.32	3.52	3.64	4.10	2.22	1.26	1.28	0.95	2.01
1953	1.00	0.93	1.34	1.44	2.27	3.19	3.77	3.38	2.26	2.07	1.33	0.87	1.99
1954	1.05	0.88	0.95	2.12	2.44	2.86	3.53	3.52	2.38	2.22	1.19	1.04	2.02
1955	1.00	0.86	1.16	1.62	2.67	2.94	3.71	3.65	3.12	1.66	0.95	1.08	2.04
1956	1.00	1.05	0.94	1.45	2.79	3.36	3.51	3.14	2.23	2.02	1.08	1.11	1.97
No.	11	11	11	11	11	11	11	11	11	11	11	11	11
Mean	1.04	1.04	1.16	1.70	2.50	3.25	3.71	3.61	2.66	1.99	1.23	1.06	2.08
Std Dev σ	0.11	0.18	0.18	0.23	0.20	0.21	0.28	0.32	0.36	0.37	0.16	0.14	0.06
C.V. (%)	11	17	15	13	8	7	8	9	14	19	13	13	3

Table 2 lists the values of precipitable water expressed in centimeters for a column from the surface to 325 mb. The yearly average was determined from the 12 monthly averages which were not adjusted for variations in the length of the months. Standard deviations and coefficients of variation were computed when the number of individual monthly values was nine or greater. Mean surface pressures and elevations were taken for the most

Table 2.—Continued.

Omaha : 94918 — Sfc. Press. 979 mb; Elev. 403 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946										2.05		0.69	
1947									2.58			0.90	
1948	0.54	0.81			1.93						1.15	0.78	
1949	0.80			1.20	2.42	3.34	3.54	3.11		1.79	1.08		
1950	0.68	0.87	0.80	1.13	1.99	2.65	2.92	2.84	2.41	1.85	0.88	0.75	1.65
1951	0.68	0.92	0.84	1.33	2.01	2.55	3.35	3.51	2.18	1.82	0.81	0.77	1.73
1952	0.72	0.87	0.91	1.12	1.99	3.44	3.44	3.39	2.21	1.13	0.97	0.81	1.75
1953	0.93	0.86	1.08	1.14	2.05	3.14	3.55	2.87	1.94	1.59	1.09	0.80	1.75
1954	0.68	0.94	0.82	1.54	1.66	3.10	3.46	3.79	2.48	1.82	1.07	0.83	1.85
1955	0.70	0.71	0.73	1.40	1.93	2.51	3.80	3.18	2.40	1.43	0.84	0.84	1.71
1956	0.80	0.78	0.84	0.97	2.27	2.77	3.00	3.02	1.99	1.69	0.99	0.85	1.66
No.	9	8	7	8	9	8	8	8	8	9	9	10	7
Mean	0.73	0.85	0.86	1.23	2.03	2.94	3.38	3.21	2.27	1.69	0.99	0.82	1.75
Std Dev σ	0.11				0.21					0.27	0.12	0.05	
C.V. (%)	15				11					16	12	6	

Portland, Maine : 14764 — Sfc. Press. 1013 mb; Elev. 20 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946	0.62	0.57	1.15	1.08	1.82	2.42	2.88	2.94	2.29	1.77	1.27	0.76	1.63
1947	0.78	0.61	0.71	1.06	2.00	2.42	3.45	3.10	2.22	1.87	0.89	0.61	1.64
1948	0.50	0.49	0.81	1.20	1.92	2.46	2.99	3.01	2.09	1.34	1.34	0.71	1.57
1949	0.77	0.69	0.79	1.11	1.75	2.53	3.10	2.89	2.27	1.69	1.07	0.79	1.62
1950	0.89	0.58	0.59	1.01	1.54	2.33	2.71	2.82	1.96	1.64	1.36	0.83	1.52
1951	0.81	0.94	0.92	1.34	1.85	2.47	3.16	3.10	2.49	1.73	1.09	0.81	1.73
1952	0.77	0.69	0.78	1 35	1.51	2.39	2.77	2.73	2.28	1.31	1.13	0.80	1.54
1953	0.83	0.72	0.88	1.29	1.96	2.17	2.83	2.42	2.16	1.68	1.27	0.92	1.59
1954	0.65	0.81	0.74	1.13	1.85	2.63	2.64	2.47	2.21	1.87	1.11	0.80	1.58
1955	0.54	0.73	0.77	1.31	1.91	2.63	3.23	3.29	2.07	1.78	1.08	0.54	1.66
1956	0.88	0.69	0.61	1.06	1.24	2.39	2.49	2.49	1.98	1.51	1.12	0.91	1.45
No.	11	11	11	11	11	11	11	11	11	11	11	11	11
Mean	0.73	0.68	0.80	1.18	1.76	2.44	2.93	2.84	2.18	1.65	1.16	0.77	1.59
Std Dev σ	0.13	0.12	0.16	0.13	0.23	0.13	0.28	0.29	0.15	0.19	0.14	0.12	0.07
C.V. (%)	18.2	17.7	19.7	11.0	13.3	5.4	9.6	10.0	6.8	11.4	12.2	15.1	4.3

Phoenix : 23183 — Sfc. Press. 972 mb; Elev. 341 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946	1.12	0.79	1.11	1.56	1.40	1.83	3.56	3.80	3.34	1.77	1.38	1.27	1.91
1947	1.07	1.13	1.31	1.22	1.88	1.92	2.72	3.78	2.76	1.88	1.35	1.11	1.84
1948	1.02	1.17	0.93	1.22	1.13	1.76	2.96	3.39	2.39	1.89	0.81	1.10	1.65
1949	0.94	0.90	1.96	1.35	1.44	2.28	3.57	2.74	3.35	1.83	1.32	1.08	1.81
1950	0.97	1.22	0.98	1.19	1.10	1.65	3.80	2.73	2.32	1.73	1.26	1.00	1.66
1951	1.14	1.18	0.85	1.41	1.42	1.22	3.20	3.61	1.96	1.61	1.46	1.26	1.69
1952	1.10	0.87	1.10	1.65	1.54	1.79	2.97	3.67	2.46	1.31	1.25	1.10	1.73
1953	1.16	0.86	1.17	1.20	1.06	1.64	3.95	2.91	1.64	1.30	1.22	0.76	1.57
1954	1.05	0.88	1.04	1.01	1.46	1.70	3.87	3.43	2.81	1.56	1.15	0.98	1.75
1955	1.12	0.72	0.79	0.82	1.22	1.55	3.32	4.32	2.10	1.63	1.13	1.34	1.67
1956	1.34	0.94	0.67	1.14	1.22	2.00	3.24	2.76	2.29	1.51	0.76	0.94	1.57
No.	11	11	11	11	11	11	11	11	11	11	11	11	11
Mean	1.09	0.97	0.99	1.25	1.35	1.76	3.38	3.38	2.49	1.64	1.19	1.09	1.72
Std Dev σ	0.10	0.17	0.18	0.23	0.24	0.27	0.41	0.52	0.54	0.21	0.22	0.17	0.11
C.V. (%)	9.4	18.0	18.2	18.7	17.6	15.2	12.0	15.3	21.5	12.8	18.7	9.2	6.1

Rapid City : 24090 — Sfc. Press. 903 mb; Elev. 966 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946	0.61	0.57	0.93	1.17	1.38	2.17	2.57	2.24	1.84	1.17	0.81	0.69	1.35
1947	0.57	0.49	0.64	1.07	1.45	2.17	2.55	2.51	1.87	1.51	0.68	0.69	1.35
1948	0.49	0.56	0.61	1.14	1.58	2.25	2.43	2.31	1.76	1.04	0.70	0.47	1.28
1949	0.51	0.46	0.75	1.05	1.73	2.15	2.39	2.20	1.60	1.30	0.89	0.60	1.30
1950	0.44	0.63	0.63	0.90	1.28	1.77	2.13	2.06	1.75	1.32	0.77	0.65	1.19
1951	0.48	0.60	0.52	0.80	1.41	1.72	2.62	2.48	1.57	1.35	0.70	0.50	1.23
1952	0.52	0.60	0.61	0.91	1.54	2.24	2.11	2.35	1.50	0.83	0.63	0.61	1.20
1953	0.75	0.66	0.71	0.86	1.36	2.24	2.55	2.50	1.42	1.23	0.88	0.61	1.31
1954	0.62	0.78	0.62	0.99	1.50	2.06	2.73	2.39	1.75	1.15	0.86	0.61	1.34
1955	0.55	0.54	0.49	0.97	1.55	2.07	2.57	2.67	1.78	1.18	0.59	0.71	1.31
1956	0.69	0.48	0.66	0.88	1.70	2.01	2.43	2.28	1.54	1.20	0.77	0.73	1.28
No.	11	11	11	11	11	11	11	11	11	11	11	11	11
Mean	0.57	0.58	0.65	0.98	1.50	2.08	2.46	2.36	1.67	1.21	0.75	0.63	1.29
Std Dev σ	0.10	0.09	0.12	0.12	0.14	0.19	0.19	0.17	0.15	0.18	0.10	0.08	0.05
C.V. (%)	17.1	16.0	17.9	12.6	9.3	8.9	7.8	7.1	8.9	14.7	13.2	12.6	3.7

Pittsburgh : 94823 — Sfc. Press. 973 mb; Elev. 353 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946	0.78	0.75	1.29	1.10	1.99	2.71	2.76	2.42		1.79	1.30	0.94	
1947	0.99	0.49	0.65	1.49	1.90	2.48	2.63	3.66	2.48	2.00		0.80	
1948	0.54	0.87	1.09	1.51	1.77	2.64	3.11	2.76		1.46	1.40	0.86	
1949	1.30	0.91	0.93	1.09	1.81	2.89	3.67	2.90	2.00	2.06	1.03	0.86	1.79
1950	1.33	0.81	0.80	1.11	2.00	2.51	2.62	2.53	2.30	1.70	1.08	0.71	1.63
1951	0.87	0.89	0.97	1.32	1.84	2.63	2.90	2.54	2.00	1.57	0.95	0.86	1.61
1952	0.91	0.79	0.91	1.40	1.82	2.56	3.03	2.65	1.99	1.20	1.13	0.90	1.61
1953	1.04	0.78	1.07	1.22	2.31	2.52	2.78	2.59	1.88	1.54	1.03	0.82	1.63
1954						2.75	2.72	3.02	2.37	1.88	1.05	0.82	
1955	0.66	0.82	0.89	1.49	2.03	2.25	3.34	3.50	2.33	1.59	1.02	0.70	1.72
1956	0.81	0.86	0.84	1.15	1.77	2.71	3.06	2.99	2.12	1.84	1.07	1.23	1.70
No.	10	10	10	10	10	11	11	11	9	11	10	11	7
Mean	0.92	0.80	0.94	1.29	1.92	2.61	2.97	2.87	2.16	1.69	1.11	0.86	1.68
Std Dev σ	0.25	0.12	0.18	0.17	0.17	0.16	0.33	0.40	0.20	0.25	0.14	0.14	
C.V. (%)	27.5	15.0	18.7	13.5	8.6	6.2	11.0	14.1	9.4	14.8	12.5	16.1	

St. Cloud : 14926 — Sfc. Press. 979 mb; Elev. 316 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946	0.55	0.57	1.19	1.19	1.57	2.58	2.90	2.69	2.18	1.68	0.97	0.71	1.57
1947	0.62	0.44								1.98	0.76	0.62	
1948	0.38	0.55	0.68	1.21	1.51	2.39	2.85	2.80		1.27	0.98	0.59	
1949	0.60	0.51	0.65	1.03	1.89	2.49	3.07	2.82	1.68	1.55	1.01	0.54	1.49
1950	0.46	0.56	0.62	0.89	1.61	2.09	2.52	2.42	2.06	1.67	0.68	0.58	1.35
1951	0.45	0.69	0.69	1.06	1.85	2.28	2.70	2.66	1.90	1.46	0.63	0.56	1.41
1952	0.56	0.67	0.59	1.12	1.53	2.63	2.81	2.71	1.84	0.91	0.86	0.73	1.41
1953	0.64	0.55	0.75	0.88	1.54	2.67	2.61	2.92	1.85	1.53	0.91	0.59	1.45
1954	0.49	0.70	0.53	1.00	1.34	2.59	2.95	2.55	2.17	1.30	0.91	0.68	1.43
1955	0.51	0.51	0.54	1.33	1.79	2.44	3.68	3.10	2.09	1.37	0.74	0.58	1.56
1956	0.62	0.47	0.60	0.87	1.61	2.69	2.81	2.78	1.78	1.57	0.87	0.71	1.45
No.	11	11	10	10	10	10	10	10	9	11	11	11	9
Mean	0.54	0.57	0.68	1.06	1.62	2.49	2.89	2.75	1.95	1.48	0.85	0.63	1.46
Std Dev σ	0.08	0.09	0.19	0.16	0.17	0.19	0.32	0.19	0.18	0.27	0.13	0.07	0.08
C.V. (%)	15.0	16.0	27.8	14.7	10.5	7.7	11.1	6.9	9.2	18.5	14.8	11.5	5.2

part from U.S. Weather Bureau *Technical Paper* No. 32. The values given are not for the period of record, but are undoubtedly a very good estimate.

Data of this type are of basic meteorological, climatological, and hydrological importance. The individual monthly values are presented because it is felt that they are of interest and could prove useful to investigators in the above-mentioned fields of study. Additional work

TABLE 2.—Continued.

San Antonio : 12921 Sfc. Press. 987 mb; Elev. 243 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946	1.59	1.68	1.77	2.68	3.50	3.82	3.80	4.15	4.45	3.40	2.40	1.92	2.93
1947	1.75	1.28	1.69	2.58	3.38	3.91	3.99	4.41	3.31	3.15	1.98	1.76	2.77
1948	1.46	1.98	1.89	2.35	3.28	3.78	4.46	3.88	3.49	2.68	1.78	1.93	2.75
1949	1.91	2.04	1.88	2.31	3.32	3.85	4.26	4.01	4.06	3.09	1.65	2.21	2.88
1950	2.61	2.25	1.71	2.63	3.39	3.87	4.16	3.86	3.99	2.65	1.82	1.36	2.86
1951	1.39	1.69	1.93	2.03	3.15	4.00	4.37	4.14	3.97	3.04	2.10	1.77	2.80
1952	2.04	1.55	1.81	2.11	2.67	3.78	4.21	4.08	3.21	1.58	2.07	1.55	2.56
1953	1.20	1.39	2.37	2.07	2.55	3.42	4.28	4.23	2.81	2.73	1.73	1.42	2.52
1954	1.75	1.36	1.58	2.65	2.89	3.73	3.74	4.09	3.46	2.97	1.68	1.47	2.61
1955	1.60	1.63	1.90	2.28	3.10	3.50	4.33	4.07	4.17	2.17	1.92	1.45	2.68
1956	1.46	1.69	1.66	2.10	2.76	3.61	3.58	3.51	3.04	2.53	1.59	1.65	2.43
No.	11	11	11	11	11	11	11	11	11	11	11	11	11
Mean	1.71	1.69	1.84	2.34	3.09	3.75	4.11	4.04	3.63	2.73	1.88	1.68	2.71
Std Dev σ	0.38	0.30	0.21	0.26	0.31	0.17	0.29	0.23	0.41	0.51	0.24	0.26	0.16
C.V.(%)	22.4	18.1	11.7	11.0	10.0	4.6	7.1	5.8	11.4	18.8	12.6	15.7	5.9

Santa Maria : 23273 Sfc. Press. 1007 mb; Elev. 74 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946	1.19	1.21	1.45	1.50	1.80	1.80	2.48	2.27	2.13	1.58	1.40	1.50	1.69
1947	1.01	1.42	1.63	1.67	1.94	2.05	1.82	2.21	2.13	2.09	1.34	1.29	1.72
1948	1.30	1.17	1.30	1.76	1.75	2.17	1.97	1.99	1.95	1.91	1.34	1.29	1.66
1949	0.97	1.24	1.51	1.70	1.95	1.97	2.19	2.18	2.10	1.70	1.65	1.20	1.70
1950	1.24	1.51	1.44	1.62	1.79	1.85	2.66	2.23	2.29	2.08	1.97	1.79	1.87
1951	1.45	1.41	1.29	1.71	1.84	1.93	2.20	2.09	2.23	1.68	1.57	1.43	1.74
1952	1.29	1.35	1.34	1.61	1.67	1.85	2.52	2.18	2.18	1.87	1.40	1.45	1.73
1953	1.59	1.00	1.29	1.51	1.38	1.79	2.25	2.04	2.12	1.46	1.67	1.12	1.60
1954	1.37	1.31	1.33	1.68	1.66	1.84	2.74	2.03	1.85	1.61	1.66	1.27	1.70
1955	1.15	1.17	1.17	1.28	1.77	1.90	1.99	2.39	2.03	1.76	1.55	1.91	1.67
1956	1.77	1.11	1.19	1.59	1.80	1.87	2.26	1.96	2.16	2.02	1.12	1.16	1.67
No.	11	11	11	11	11	11	11	11	11	11	11	11	11
Mean	1.30	1.26	1.36	1.60	1.76	1.91	2.28	2.14	2.11	1.80	1.52	1.40	1.71
Std Dev σ	0.24	0.15	0.14	0.13	0.16	0.11	0.29	0.13	0.13	0.22	0.23	0.26	0.07
C.V.(%)	18	12	10	8	9	6	13	6	6	12	15	18	4

San Diego : 93112 Sfc. Press. 1014 mb; Elev. 13 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946	1.13	1.12	1.53	1.67	1.79	1.94	2.77	3.39	3.33	2.39	2.07	1.93	2.09
1947	0.93	1.32	1.54	1.58	1.91	2.28	2.02	2.57	3.15	2.01	1.48	1.33	1.84
1948	1.23	1.30	1.43	1.63	1.51	2.06	2.08	2.21	1.84	1.88	1.07	1.21	1.62
1949	0.96	1.15	1.32	1.60	1.62	2.12	2.62	2.17	2.39	1.77	1.71	1.37	1.73
1950	1.42	1.52	1.56	1.65	1.56	1.82	3.37	2.47	2.38	2.07	1.89	1.70	1.95
1951	1.48	1.39	1.23	1.99	1.80	1.78	3.03	2.74	2.46	2.13	1.78	1.63	1.95
1952	1.40	1.46	1.48	1.92	1.74	1.94	2.79	3.20	2.88	2.06	1.64	1.54	2.00
1953	1.70	1.18	1.41	1.75	1.64	2.03	3.38	2.68	2.39	1.98	1.96	1.23	1.94
1954	1.53	1.39	1.65	1.68	1.97	2.07	3.41	2.34	2.38	1.71	1.66	1.42	1.93
1955	1.37	1.14	1.34	1.22	1.83	1.96	2.77	3.87	2.49	1.90	1.57	1.82	1.94
1956	1.84	1.18	1.13	1.70	1.76	1.72							
No.	11	11	11	11	11	11	10	10	10	10	10	10	10
Mean	1.36	1.29	1.42	1.67	1.74	1.97	2.82	2.76	2.57	1.99	1.68	1.52	1.90
Std Dev σ	0.28	0.14	0.15	0.20	0.14	0.17	0.50	0.56	0.43	0.19	0.27	0.25	0.14
C.V.(%)	21	11	11	12	8	9	18	20	17	10	16	16	7

Sault St. Marie : 14847 Sfc. Press. 988 mb; Elev. 221 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946	0.52	0.44	0.93	0.93	1.37	2.08	2.50	2.24	1.98	1.62	0.98	0.60	1.35
1947	0.51	0.46	0.53	0.82	1.23	1.97	2.68	3.13	2.19	2.05	0.79	0.60	1.41
1948	0.39	0.47	0.60	1.19	1.30	1.93	2.41	2.55	1.95	1.31	1.16	0.63	1.32
1949	0.67	0.59	0.66	0.92	1.45	2.43	2.63	2.42	1.74	1.52	0.83	0.62	1.37
1950	0.61	0.46	0.54	0.77	1.46	1.91	2.27	2.05	1.86	1.58	0.86	0.61	1.25
1951	0.54	0.70	0.75	1.04	1.61	1.98	2.32	2.19	1.78	1.55	0.64	0.55	1.30
1952	0.62	0.51	0.65	1.08	1.41	2.22	2.71	2.39	2.10	0.98	1.02	0.78	1.37
1953	0.67	0.59	0.79	0.92	1.44	2.29	2.47	2.53	2.03	1.45	1.03	0.73	1.41
1954	0.50	0.65	0.54	0.98	1.23	2.52	2.29	2.33	2.10	1.50	0.99	0.58	1.35
1955	0.51	0.50	0.59	1.26	1.56	2.36	2.99	2.78	1.76	1.58	0.84	0.58	1.44
1956	0.62	0.53	0.48	0.83	1.18	2.45	2.27	2.44	1.70	1.53	0.97	0.68	1.31
No.	11	11	11	11	11	11	11	11	11	11	11	11	11
Mean	0.56	0.54	0.64	0.98	1.39	2.19	2.50	2.46	1.93	1.52	0.92	0.63	1.35
Std Dev σ	0.09	0.09	0.13	0.16	0.14	0.23	0.22	0.30	0.17	0.26	0.14	0.07	0.06
C.V.(%)	15.3	16.4	20.8	16.1	10.3	10.7	9.0	12.1	9.0	16.9	15.6	10.6	4.4

San Juan : 11636 Sfc. Press. 1014 mb; Elev. 19 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946	3.13	2.96	3.00		4.11	4.20	3.84	4.27	4.67	4.95	4.38	3.81	
1947	3.39	3.51	2.93	3.10	3.71	3.86	3.69	3.91	4.55	4.56	3.84	3.44	3.71
1948	3.30	3.01	3.05	3.28	4.31	4.35	4.32	4.33	4.47	4.48	4.43	3.59	3.91
1949	2.93	2.85	3.35	3.11	3.98	4.09	4.13	4.33	4.57	4.39	4.13	3.84	3.81
1950	3.03	3.50	3.01	3.41	3.86	4.16	4.12	4.51	4.47	4.71	4.17	3.69	3.88
1951	3.25	2.66	2.83	3.58	4.63	4.38	4.76	4.68	4.93	4.57	4.32	3.77	4.03
1952	3.27	3.30	3.29	4.16	4.35	4.33	4.61	4.41	4.61	4.42	3.99	3.17	3.99
1953	3.22	2.99	3.11	3.33	4.21	4.62	4.32	4.14	4.28	4.03	4.21	3.81	3.85
1954	3.14	3.67	3.12	3.41	4.13	4.08	4.07	4.44	4.50	4.23	3.95	3.49	3.85
1955	2.94	2.99	2.67	3.06	3.92	4.04	3.98	4.36	4.60	4.57	3.76	3.59	3.71
1956													
No.	10	10	10	9	10	10	10	10	10	10	10	10	9
Mean	3.16	3.14	3.04	3.38	4.12	4.21	4.18	4.34	4.57	4.49	4.12	3.62	3.86
Std Dev σ	0.15	0.33	0.20	0.34	0.27	0.22	0.33	0.21	0.17	0.25	0.23	0.21	0.12
C.V.(%)	4.9	10.5	6.6	10.1	6.5	5.1	7.9	4.8	3.7	5.6	5.5	5.8	3.1

Seattle : 24244 Sfc. Press. 1015 mb; Elev. 124 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946													
1947													
1948													
1949	0.85	1.06	1.29	1.43	1.65	1.92	2.32	2.35	2.23	1.62	1.89	1.18	1.65
1950	0.65	1.10	1.23	1.20	1.62	2.27	2.40	2.67	2.02	1.64	1.49	1.57	1.66
1951	0.98	1.21	1.02	1.21	1.72	2.00	2.30	2.43	2.21	1.76	1.37	1.02	1.60
1952	1.01	1.16	1.11	1.36	1.65	1.98	2.20	2.39	2.12	1.87	1.24	1.24	1.61
1953	1.52	1.20	1.26	1.52	1.80	2.03	2.18	2.61	2.16	1.95	1.63	1.41	1.77
1954	1.06	1.48	0.99	1.27	1.67	2.02	2.10	2.56	2.37	1.73	1.94	1.33	1.71
1955	1.26	0.99	1.03	1.19	1.60	2.33	2.52	2.14	2.18	1.89	1.21	1.16	1.63
1956	1.13	1.02	1.12	1.36	1.72	2.09							
No.	8	8	8	8	8	8	7	7	7	7	7	7	7
Mean	1.06	1.15	1.13	1.32	1.68	2.08	2.29	2.45	2.18	1.78	1.54	1.27	1.66
Std Dev σ													
C.V.(%)													

dealing with the distribution and variaton of precipitable water data as defined by these values has been presented elsewhere [4].

ACKNOWLEDGMENTS

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TABLE 2.—Concluded.

Spokane : 24157 Sfc. Press. 933 mb; Elev. 722 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946	0.86	0.83	1.00	1.19	1.35	1.68	1.80	1.73	1.71	1.11	0.97	0.95	1.27
1947	0.74	0.85	0.99	[illegible]	1.54	1.76	1.81	1.77	1.85	1.72	1.03	0.91	1.34
1948	0.75	0.68	0.70	0.97	1.54	2.14	1.82	1.85	1.48	1.12	0.90	0.59	1.21
1949	0.48	0.63	0.91	0.99	1.43	1.40	1.65	1.67	1.60	1.06	1.33	0.70	1.15
1950	0.41	0.86	0.85	0.90	1.12	1.87	1.76	1.78	1.35	1.43	0.95	1.11	1.20
1951	0.65	0.71	0.71	0.87	1.28	1.50	1.75	1.65	1.52	1.26	0.96	0.70	1.13
1952	0.68	0.71	0.76	1.00	1.30	1.57	1.51	1.61	1.53	1.18	0.87	0.92	1.14
1953	1.08	0.80	0.82	0.97	1.22	1.57	1.35	1.80	1.39	1.36	1.06	0.91	1.19
1954	0.70	0.89	0.66	0.78	1.23	1.45	1.67	1.75	1.55	1.15	1.28	0.84	1.16
1955	0.79	0.61	0.56	0.82	1.15	1.55	2.05	1.25	1.55	1.48	0.77	0.78	1.11
1956	0.77	0.64	0.75	1.00	1.47	1.62	1.91	1.80	1.40	1.26	1.02	0.95	1.22
No.	11	11	11	11	11	11	11	11	11	11	11	11	11
Mean	0.72	0.75	0.79	0.97	1.33	1.65	1.74	1.70	1.54	1.29	1.01	0.85	1.19
Std Dev σ	0.18	0.11	0.14	0.13	0.15	0.22	0.18	0.17	0.15	0.19	0.16	0.15	0.07
C.V. (%)	24.9	14.1	17.3	13.2	11.2	13.1	10.6	[illegible]	9.5	15.2	16.2	17.3	6.0

Tatoosh Island : 24240 Sfc. Press. 1012 mb; Elev. 31 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946	1.23	1.17	1.16	1.31	1.65	2.00	2.25	2.06	2.06	1.50	1.20	1.23	1.57
1947	1.07	1.35	1.36	1.48	1.71	1.98	2.17	2.01	1.88	1.73	1.45	1.39	1.63
1948	1.21	1.10	1.09	1.11	1.64	2.13	2.14	2.36	1.99	1.64	1.21	0.98	1.55
1949	0.86	1.02	1.22	1.41	1.62	1.78	2.11	2.19	2.12	1.69	1.89	1.15	1.59
1950	0.64	1.21	1.13	1.18	1.47	2.18	2.25	2.41	1.97	1.58	1.27	1.56	1.57
1951	1.09	1.11	1.01	1.13	1.61	1.90	2.20	2.00	2.22	1.75	1.36	1.05	1.54
1952	1.07	1.13	1.12	1.35	1.49	1.68	2.11	2.22	2.06	2.01	1.34	1.26	1.57
1953	1.48	1.15	1.14	1.24	1.60	1.84	2.12	2.53	2.09	1.93	1.58	1.44	1.68
1954	0.98	1.41	0.90	1.12	1.48	1.74	2.07	2.37	2.20	1.73	1.80	1.31	1.59
1955	1.21	1.01	1.01	1.06	1.34	2.11	2.16	2.08	2.04	1.74	1.17	1.07	1.50
1956	1.05	1.02	1.06	1.28	1.53	1.88	2.08	2.30	2.07	1.54	1.48	1.39	1.56
No.	11	11	11	11	11	11	11	11	11	11	11	11	11
Mean	1.08	1.15	1.11	1.24	1.56	1.93	2.15	2.23	2.06	1.71	1.43	1.26	1.58
Std Dev σ	0.22	0.13	0.12	0.13	0.11	0.17	0.06	0.18	0.09	0.15	0.24	0.18	0.03
C.V. (%)	20.0	11.0	11.0	10.7	7.0	8.7	2.8	8.0	4.3	8.8	16.7	14.6	2.0

Tampa : 12842 Sfc. Press. 1017 mb; Elev. 7 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946	2.30	2.21	2.21	2.29	3.83	4.41	4.66	4.80	4.58	3.40	3.38	2.37	3.37
1947	2.96	1.76	2.09	3.51	3.59	4.40	4.40	4.55	4.55	3.65	3.28	2.69	3.45
1948	2.19	2.57	3.08	2.95	3.06	4.03	5.00	4.85	4.45	2.98	3.24	2.76	3.43
1949	2.33	2.77	2.10	2.67	2.88	4.10	4.72	4.77	4.50	3.89	1.97	2.46	3.26
1950	2.46	2.05	2.36	2.10	3.31	4.17	4.50	4.51	4.06	3.59	2.34	1.99	3.12
1951	1.83	1.85	2.28	2.52	2.95	3.99	4.90	5.10	4.81	3.52	2.33	2.60	3.22
1952	2.07	2.17	2.65	2.16	3.16	4.41	4.53	4.85	4.83	3.76	2.38	1.95	3.24
1953	2.03	2.34	2.61	2.53	3.21	4.38	4.67	5.00	4.55	2.99	2.62	2.68	3.30
1954	1.88	1.78	2.11	3.40	3.15	4.20	4.84	4.61	4.63	2.97	2.32	1.78	3.14
1955	2.03	2.05	2.31	2.59	3.27	3.52	4.79	4.90	4.74	3.06	2.30	2.35	3.16
1956	1.54	2.36	1.89	2.35	3.65	3.78	4.12	4.58	3.87	3.19	2.01	2.21	2.96
No.	11	11	11	11	11	11	11	11	11	11	11	11	11
Mean	2.15	2.17	2.34	2.64	3.28	4.13	4.65	4.78	4.51	3.36	2.56	2.35	3.24
Std Dev σ	0.37	0.32	0.34	0.47	0.30	0.28	0.25	0.18	0.30	0.34	0.51	0.33	0.15
C.V. (%)	17.4	14.7	14.4	17.6	9.2	6.7	5.5	3.8	6.7	10.0	19.8	14.2	4.9

Washington, D. C. : 93722 Sfc. Press. 1011 mb; Elev. 88 m

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
1946	1.01	0.94	1.48	1.47	2.48	2.99	3.38	3.22	3.00	1.97	1.51	1.14	2.05
1947	1.30	0.60	0.82	1.84	2.34	2.97	3.32	4.01	3.07	2.39	1.24	0.88	2.07
1948	0.77	1.04	1.31	1.84	2.38	3.29	3.73	3.38	2.64	1.71	1.78	1.08	2.08
1949	1.49	1.18	1.07	1.46	2.47	3.45	4.39	3.70	2.68	2.50	1.29	1.11	2.23
1950	1.64	1.05	0.97	1.33	2.49	2.96	3.57	3.40	3.04	2.12	1.32	0.86	2.06
1951	0.95	1.05	1.14	1.48	2.21	3.24	3.57	3.28	2.69	2.14	1.20	1.15	2.01
1952	1.25	0.98	1.19	1.92	2.29	3.18	3.67	3.56	2.45	1.47	1.41	1.06	2.04
1953	1.30	1.02	1.28	1.56	2.95	3.07	3.46	3.47	2.83	1.86	1.28	1.06	2.09
1954	0.98	0.94	1.02	1.99	2.18	2.89	3.27	3.65	2.78	2.14	1.28	0.94	2.01
1955	0.72	0.96	1.07	1.86	2.20	2.61	4.12	4.31	2.95	1.90	1.23	0.77	2.06
1956	0.97	1.06	1.03	1.38	2.30	3.27	3.77	3.22	2.62	2.22	1.23	1.43	2.04
No.	11	11	11	11	11	11	11	11	11	11	11	11	11
Mean	1.13	0.98	1.13	1.65	2.39	3.08	3.66	3.56	2.80	2.04	1.34	1.04	2.07
Std Dev σ	0.26	0.14	0.19	0.24	0.22	0.23	0.34	0.34	0.21	0.30	0.17	0.18	0.07
C.V. (%)	22.9	14.4	16.5	14.8	9.1	7.4	9.3	9.5	7.4	14.6	12.7	17.0	3.4

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REFERENCES

1. S. B. Solot, "Computation of Depth of Precipitable Water in a Column of Air," *Monthly Weather Review*, vol. 67, No. 4, Apr. 1939, pp. 100–103.
2. A. L. Shands, "Mean Precipitable Water in the United States," U.S. Weather Bureau *Technical Paper* No. 10, Washington, D.C., 1949.
3. B. Ratner, "Upper Air Average Values of Temperature, Pressure, and Relative Humidity over the United States and Alaska," U.S. Weather Bureau *Technical Paper* No. 6, Washington D.C., 1945.
4. C. H. Reitan, "Distribution of Precipitable Water Vapor over the Continental United States," *Bulletin of the American Meteorological Society*, vol. 41, No. 2, Feb. 1960, pp. 79–87.

THE WEATHER AND CIRCULATION OF JANUARY 1960

Another January With Atlantic Blocking

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1. INTRODUCTION

In all but one year since 1954, mean 700-mb. maps for January have contained centers of large positive height anomaly near Davis Strait with negative anomalies to the south. This pattern of vigorous blocking over the western Atlantic Ocean was again observed during January 1960 (fig. 1). The mean for this January particularly resembled that for January 1955 [1]. Furthermore, both maps evolved in the same manner over the contiguous United States, with a trough in the West and a ridge in the East in the first half-month, a ridge in the West and a trough in the East in the second (fig. 2, and fig. 3 of [1]).

Because of its transitional circulation, January 1960 established few new records of extreme weather for the month. However, new totals for excessive precipitation amounts were recorded in Iowa, and for deficient amounts in Washington and extreme southern Florida. Previous marks of high and low temperature for the month were unchallenged, but the warm maritime regime which had characterized December 1959 [2] yielded to a January circulation favoring colder temperatures.

2. OTHER ASPECTS OF THE GENERAL CIRCULATION

Figure 3A illustrates the extensive increase of height anomalies over northern latitudes from December to January, especially in centers near Iceland, the Arctic Ocean, and the Gulf of Alaska. With the extensive blocking at high latitudes, negative changes appeared at middle latitudes. The resulting channel of negative anomalies was remarkably continuous (fig. 1), being interrupted at only one place by a weak positive tongue south of Alaska.

Figure 3B illustrates mean 700-mb. height changes from the first to the second half of January. The broad zone of height rises from the Labrador Sea westward and the flanking areas of falls accent the progress of blocking within the month. A distinct westward shift is evidenced by the intensity and the remarkable extent of the negative change in the Pacific.

Blocking was prevalent in Canada during December 1959, and it had spread westward to the Gulf of Alaska and the Siberian Peninsula near the end of that month. By January 10 the Siberian segment had retrograded about the pole, and a positive center had become well established in the Greenland Sea (from 5-day means, not shown). The center continued to grow and move westward, reaching maximum 5-day mean intensity over Baffin Island around January 18. Thereafter, a surge spread rapidly to western Canada and across the Polar Basin to northern Greenland the following week. While considerable similarity existed in the initial state and subsequent behavior of blocking in December as compared to January, there was one important difference. A large portion of the December surge joined and amplified the subtropical ridge in the Gulf of Alaska. That strong mean ridge and the trough downstream from it were prominent features of the early January circulation (fig. 2A) and strongly influenced the weather of the United States during the first half-month.

Accompanying the increasing positive anomalies at high latitudes was a southward depression of the mean westerlies. Solid arrows tracing the observed axes of maximum westerlies in figure 4 are south of the normal axes (dashed) over much of the hemisphere. The southward shift was most pronounced over the extreme eastern Pacific, the contiguous United States, and the Atlantic (where the strongest blocking prevailed). Normal and observed axes nearly coincided over most of the Pacific, and wind speeds there generally exceeded normal (fig. 4B). Southward from 40° N. in the Atlantic, positive departures were greater, exceeding 7 m.p.s. in a rather large area enclosed by the 20 m.p.s. isotach south of Newfoundland. On the other hand, negative departures of as much as 12 m.p.s. occurred just north of Newfoundland.

The mean wind speed profile of figure 5 helps to summarize the effects of blocking through a segment of the hemisphere from 175° E. eastward to 5° W. Depression of the westerlies is shown in this figure as a southward displacement of the wind field at all latitudes south of 65° N. The mean westerly deficit north of 41° N. and the compensating excess to the south are typical of widespread blocking at high latitudes [3].

The strength of the temperate westerlies diminished as height anomalies increased north of 55° N. The curve of figure 6 depicts the recovery of the 5-day mean zonal index from a late December decline to a maximum in early January. This was followed by a sharp drop during

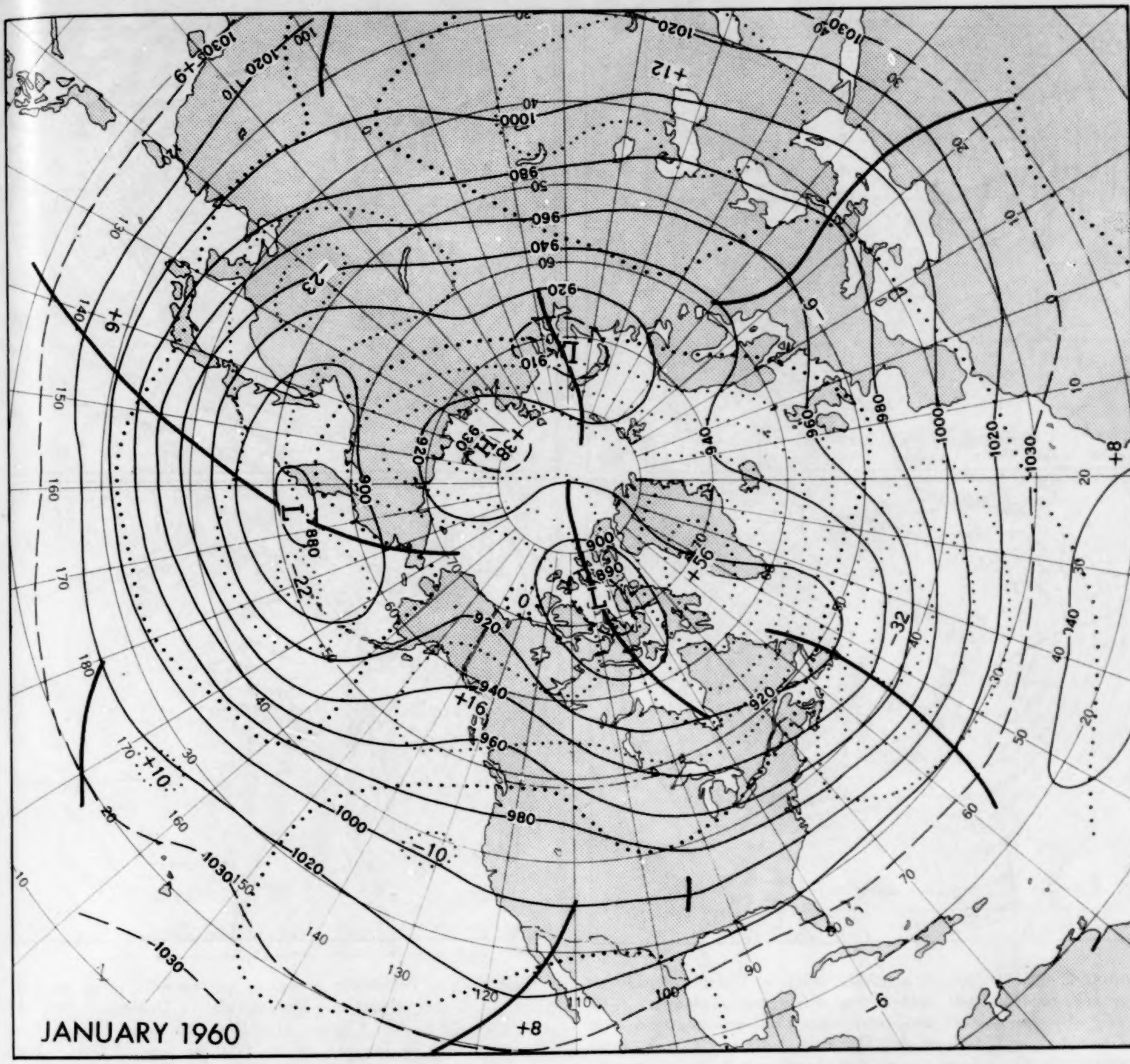

Figure 1.—Mean 700-mb. contours (solid) and height departures from normal (dotted), both in tens of feet, for January 1960. Troughs are indicated by heavy solid lines. Positive anomalies predominated at polar latitudes, and the surrounding channel of negative anomalies was nearly continuous around the hemisphere.

the middle of January to 5.9 m.p.s., the lowest value observed since August 1959. Except for a brief period, the index remained below normal, and the monthly mean value diminished from 1.9 m.p.s. above normal in December to 2.4 m.p.s. below in January.

Subtropical westerlies increased correspondingly from 2.8 m.p.s. below normal to 2.2 m.p.s. above. Temperature anomalies in the contiguous United States in general corresponded to the 5-day mean index, by cooling as the index fell and warming as it rose.

3. TEMPERATURES

Woffinden [2] described the abrupt change to a warm December from a cold fall season. Cooling began in late December, however, and was predominant thereafter with short-period variations over much of the nation until late January. Temperature persistence between the two months was 72 percent (within change limits of one class [1]), which conformed closely to the average 71 percent for

[1] Temperature classes are much above and much below normal (12½ percent occurrence each) and above, near normal, and below (25 percent occurrence each).

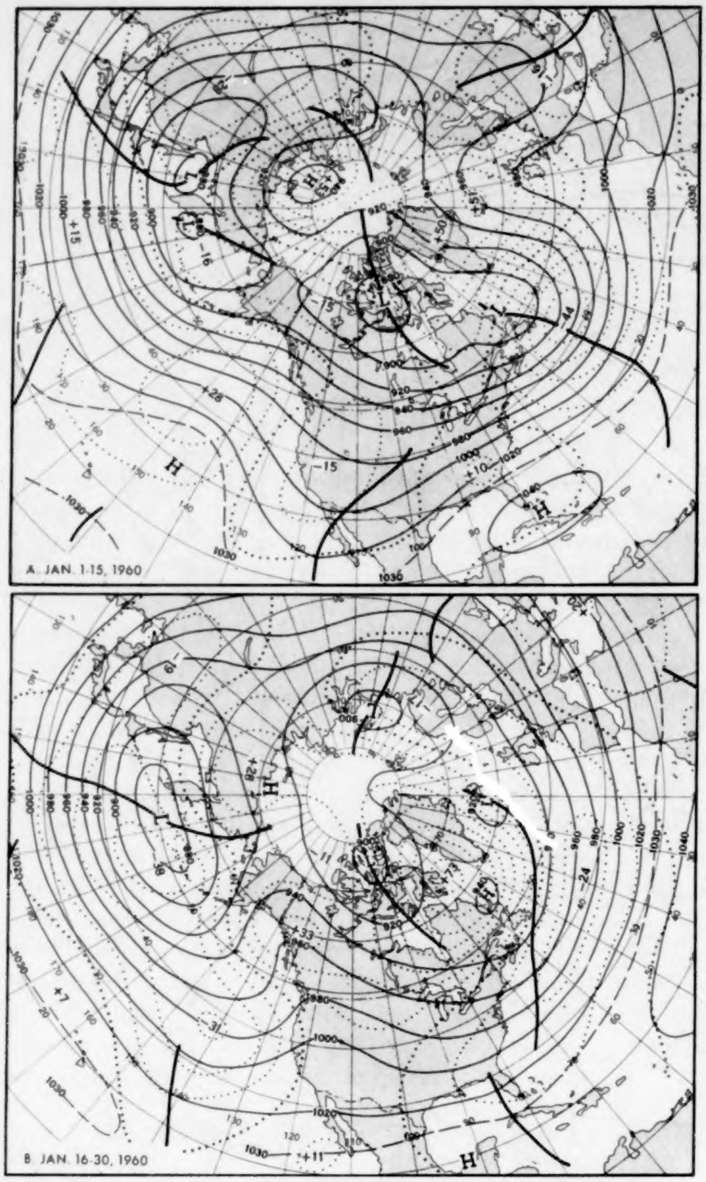

FIGURE 2.—Mean 700-mb. contours (solid) and height departures from normal (dotted), both in tens of feet, for (A) January 1–15, and (B) January 16–30, 1960. Blocking was centered over Greenland and Iceland for the first half-month, and large-amplitude waves were observed over the eastern Pacific and the contiguous United States. During the second half blocking was strongest from Davis Strait to the Yukon, and the trough-ridge structure over the United States reversed phase.

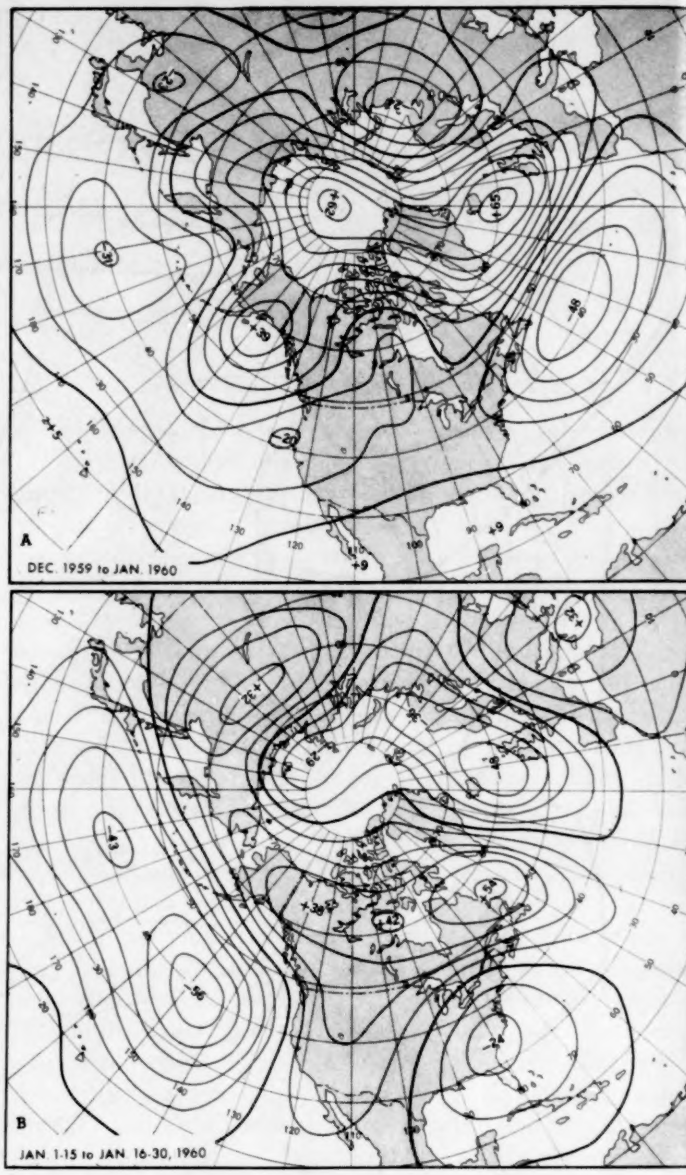

FIGURE 3.—(A) Difference in tens of feet between mean monthly 700-mb. height departures from normal of December 1959 and January 1960. (B) Change in half-month mean heights from January 1–15 to January 16–30, 1960 (in tens of feet). Both charts have large rises at high latitudes and falls at middle latitudes, indicating the progressive increase of blocking from month to month and through January.

1942–54 determined by Namias [4]. However, 73 of 100 well-distributed stations cooled by one class or more, and only 21 averaged above normal in January.

This cool pattern (fig. 7A) agreed well with the low zonal index and depressed westerlies of the mean circulation. Below-normal temperatures across the southern portion of the United States were associated with a channel of negative height anomaly (fig. 1). Combined effects of the abnormally strong ridge over western British Columbia and the mean trough in the Southwest were related to below normal temperatures from the Great Basin northward. Some of the cold air from western Canada pushed southward east of the Continental Divide to help produce cold anomalies in the Central Plains.

Above-normal temperatures in the Northeast were related to the easterly anomalous flow (fig. 1) from a

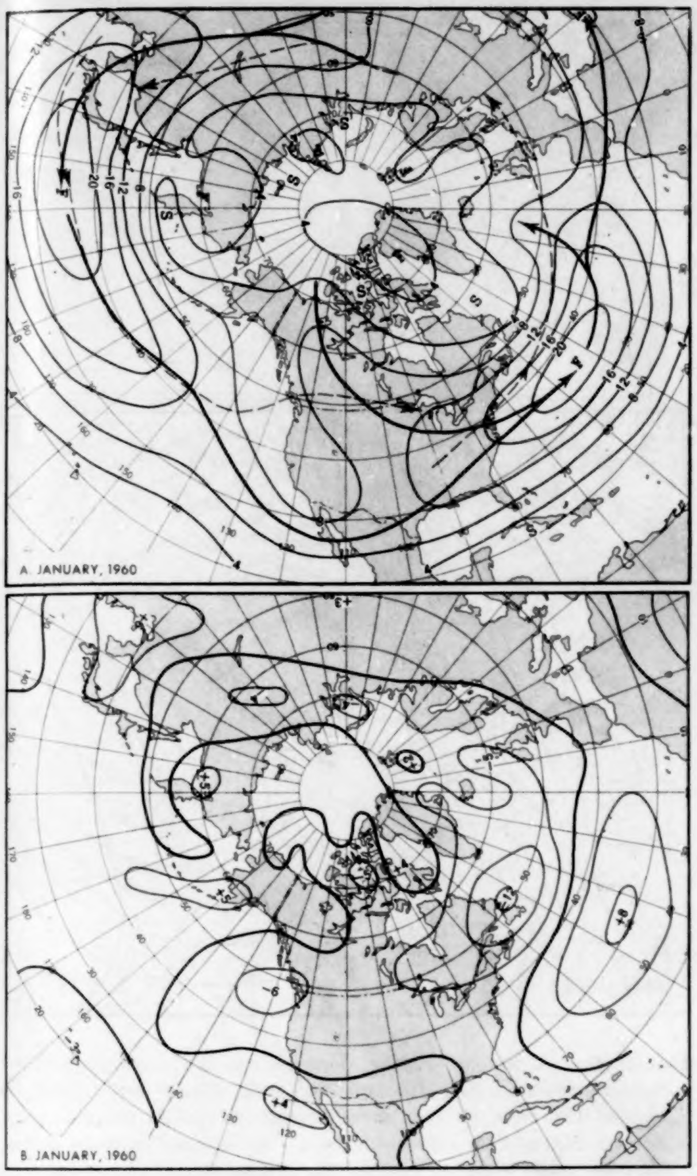

FIGURE 4.—(A) Mean isotachs in meters per second of 700-mb. wind speed during January 1960 and (B) departure from normal wind speed. Solid arrows in (A) indicate observed axes of maximum wind speed, and dashed arrows the normal. This month's axes were generally south of normal except in the Pacific.

maritime, rather than a continental, source region. Temperatures along the west coast of the contiguous United States averaged a little above normal due to strong warming in southerly flow during the second half of the month. In southern California, however, the warming was not sufficient to compensate for cool weather during the first half of the month. A near-normal average at San Diego was the first monthly mean temperature since March 1958 which was not much above normal. The monthly average was close to the normal at Los Angeles and below at Santa Maria, so that the

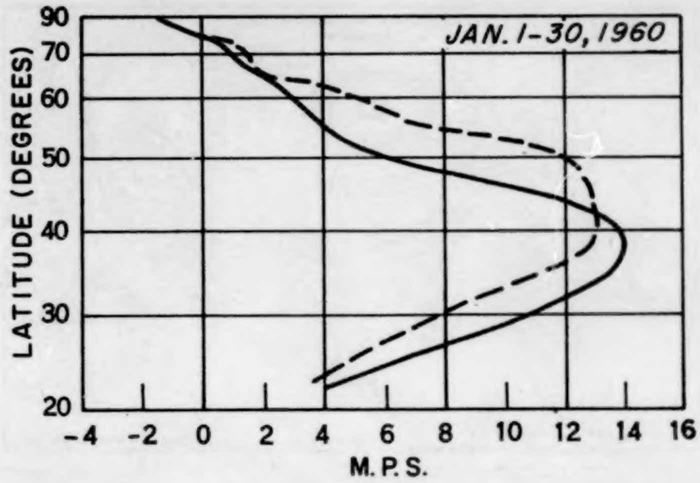

FIGURE 5.—Mean 700-mb. zonal wind speed profiles in the Western Hemisphere for January 1960 (solid) and January normal (dashed). The displacement of the observed profile southward from normal south of 65° N. was associated with blocking.

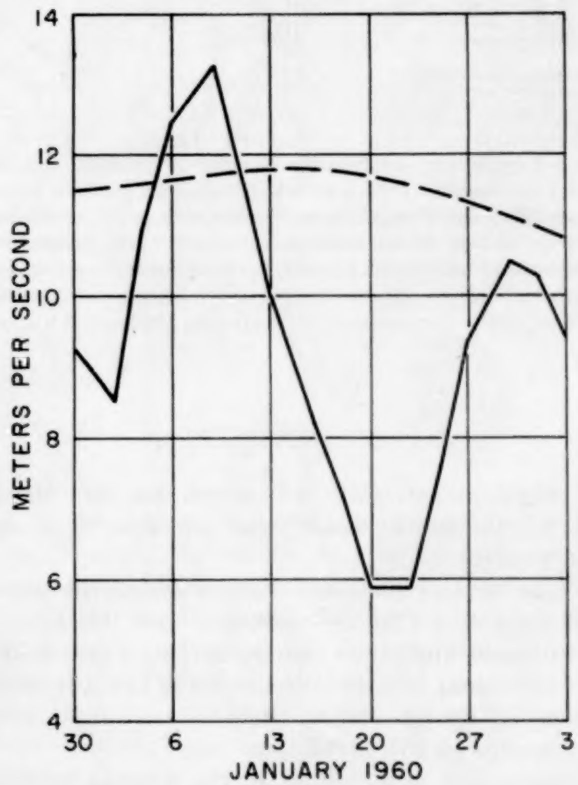

FIGURE 6.—Time variation of zonal index in meters per second for the Western Hemisphere in the latitude belt 35° to 55° N. A complete oscillation of the index occurred in January 1960, reflecting the transitional nature of the circulation. The mean index for the month was 2.4 m.p.s. below normal (dashed curve).

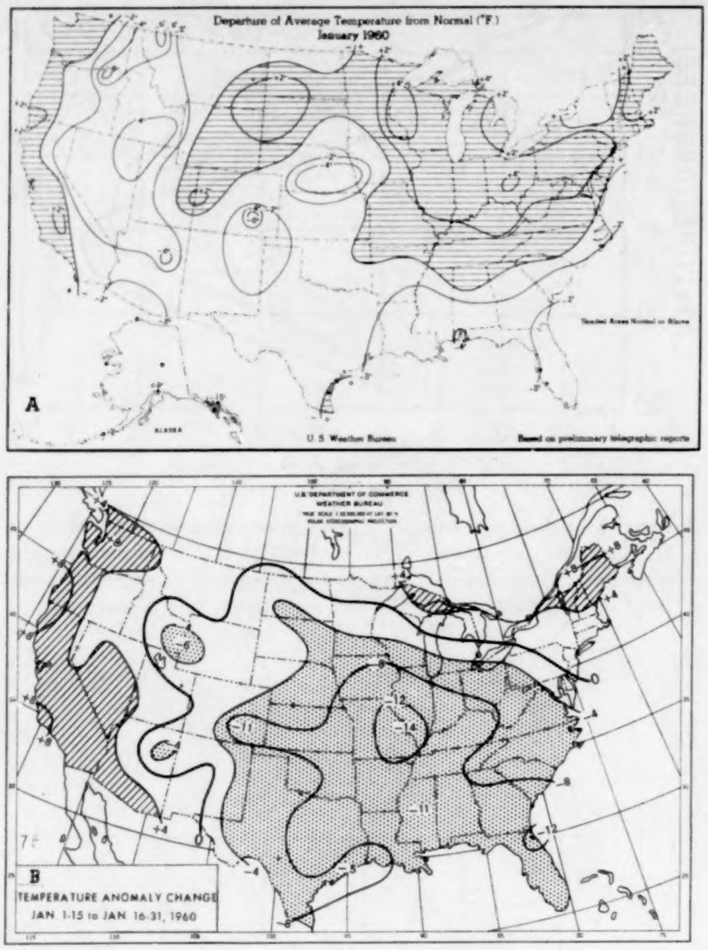

Figure 7.—(A) Departure from normal of average temperature (° F.) for January 1960. Hatching indicates positive departures (from [6]). (B) Temperature anomaly change (° F.) from January 1–15 to January 16–30, 1960. Hatching indicates positive change of 4° F. or more; stippling, negative change of the same magnitude. A circulation reversal encouraged southward penetration of cold air east of the Continental Divide during the second half-month.

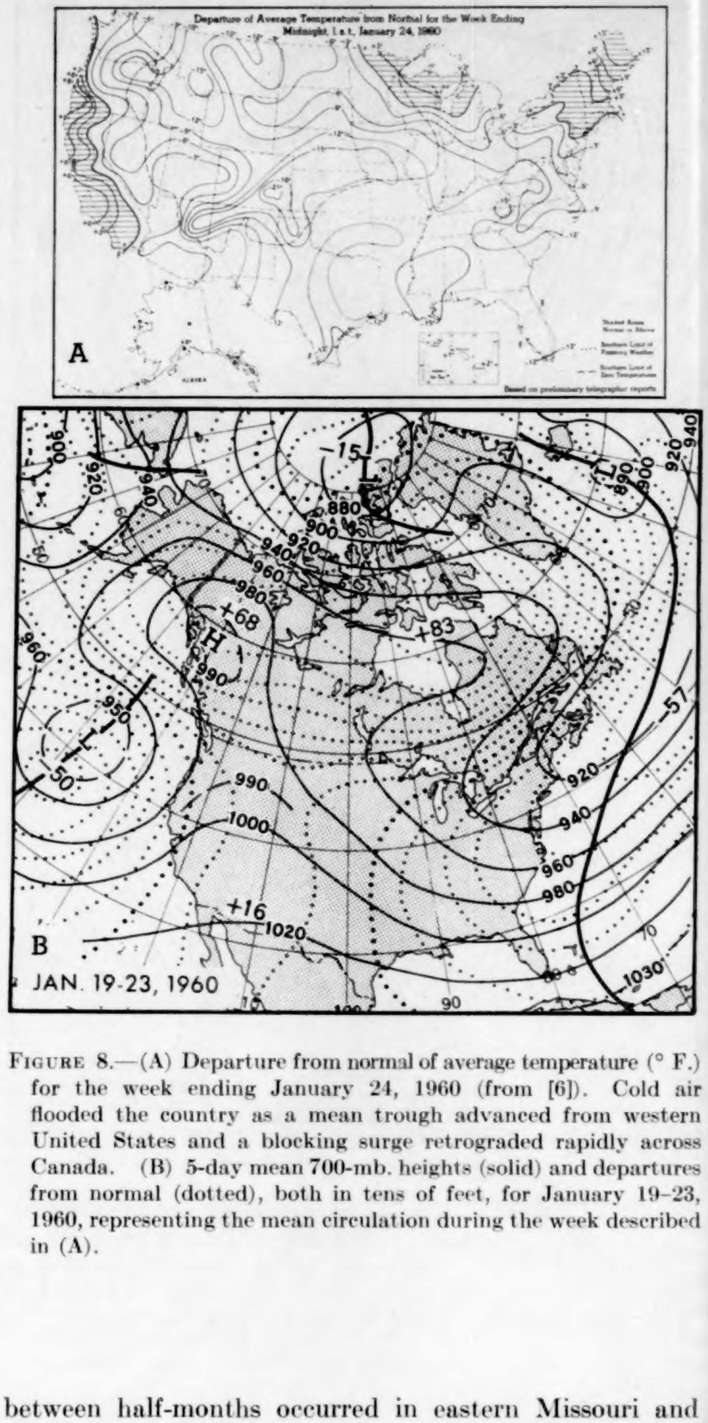

Figure 8.—(A) Departure from normal of average temperature (° F.) for the week ending January 24, 1960 (from [6]). Cold air flooded the country as a mean trough advanced from western United States and a blocking surge retrograded rapidly across Canada. (B) 5-day mean 700-mb. heights (solid) and departures from normal (dotted), both in tens of feet, for January 19–23, 1960, representing the mean circulation during the week described in (A).

long period of extremely warm temperatures along the southern California coast was at least temporarily interrupted [2].

In view of the circulation changes within the month, it is not surprising that the anomalies just described were rather weak and their configuration was ill-defined. Some additional information about the temperatures can be obtained by considering them in relation to shorter-period means of the circulation.

Temperatures were coldest in the western trough and warmest in the eastern ridge during the first half-month. Around midmonth the mean trough moved rapidly eastward, the zonal index continued to drop, and cold air flooded most of the country. Figure 7B outlines the change which resulted. The area of greatest cooling between half-months occurred in eastern Missouri and southwestern Illinois. There the mean 700-mb. flow (fig. 2) shifted to northwesterly and became more cyclonic, while the anomalous flow reversed from a southerly to a northerly direction.

Cold was most intense and widespread during the week ending January 24 (fig. 8A). At this point the mean trough was off the east coast (fig. 8B), blocking over Canada was at a maximum, and the zonal index reached its minimum for the month. High sea level pressure attending the cold air effectively inhibited the march of surface cyclones across the contiguous United States, and

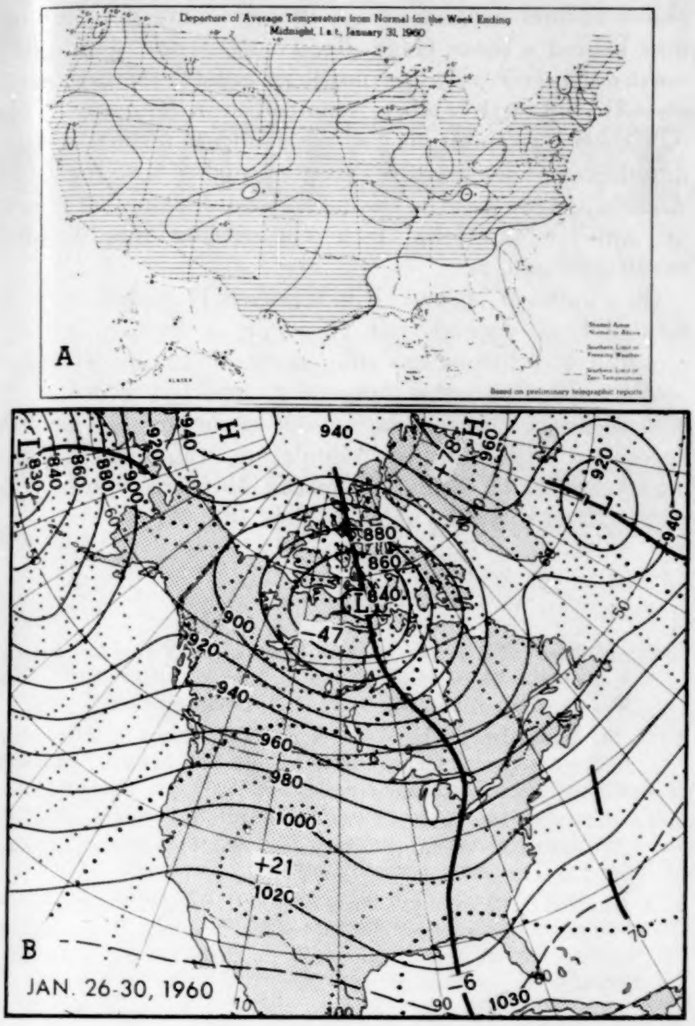

FIGURE 9.—(A) Departure from normal of average temperature (° F.) for the week ending January 31, 1960 (from [6]). Rapid warming followed the cold outbreak of the previous week (fig. 8). (B) The 5-day mean 700-mb. height (solid) and height anomaly (dotted), both in tens of feet for January 26–30, 1960, show the rapidly altered circulation which accompanied the warming.

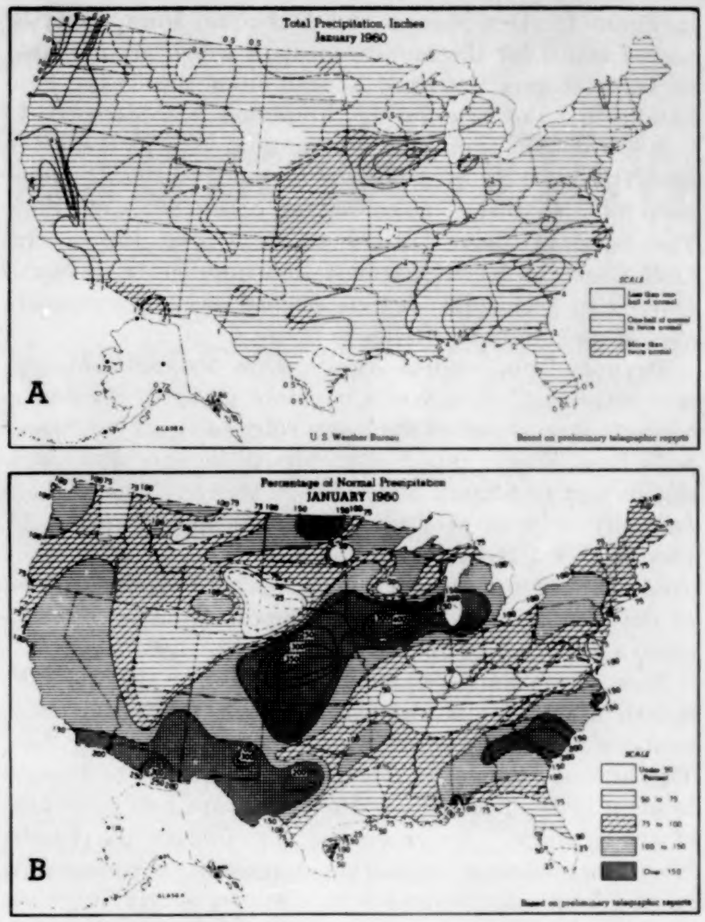

FIGURE 10.—(A) Total precipitation in inches for January 1960 (from [6]). Note the small size of unhatched areas representing less than half of normal. These areas are enclosed by lines labeled 50 on (B), the percentage of normal precipitation for January 1960 (from [6]). Outstanding feature of precipitation pattern is the streak of above normal from the Southwest to Michigan.

none was reported west of the Mississippi River from the 17th to the 27th (see Chart X of [5]).

Figure 9 shows the remarkable warming in the week that followed. Anomaly patterns this warm are typically attended by fast westerlies of small amplitude over the contiguous United States and below normal 700-mb. heights over Alaska and northwestern Canada. Such a circulation was quickly accomplished in this instance by the southward migration of a deepening polar vortex as blocking retrograded from Canada. A general increase of the westerlies occurred over the Western Hemisphere (see the index curve of fig. 6), and a 5-day mean trough was eliminated in the eastern Pacific as mean wavelengths increased.

4. PRECIPITATION

Low index mean circulations have been empirically described as "cold and wet," and this January conformed to that description. It was not only colder than normal, as indicated in the previous section, but also wetter than normal. Of the usual 100 well-distributed stations, only 15 reported precipitation totals in the light class, while 51 had moderate precipitation, and 34 had heavy. Since each class should normally occur one-third of the time, the occurrence of light had less than half its usual frequency.

Most of the precipitation pattern agreed well with features of the mean monthly circulation. A band of substantial (and above normal) amounts reaching from southern Arizona to Iowa (fig. 10) can be attributed to cyclonic activity along and east of the mean trough shown

in figure 1. Des Moines and Dubuque, Iowa, reported record totals for the month, most of which accumulated as three storms traversed a path from the Texas Panhandle to Lake Erie during the period from January 11 to 18. At Dubuque the 24-hour total of 3.75 inches on the 11th and 12th exceeded the previous wettest January total of 3.45 inches measured in both 1861 and 1869. The band of above normal amounts from the central Gulf Coast to North Carolina and another from North Dakota to Pennsylvania were aligned along the separate axes of maximum westerlies in figure 4.

Dryness from central Montana to western Nebraska occurred in the absence of a moisture source in the northwesterly flow ahead of the mean ridge of figure 1. Stampede Pass, Wash., reported the driest January on record, due in part to a mean deficit in the westerly winds which normally help to produce orographic precipitation. In Florida, West Palm Beach and Key West reported their driest Januarys on record. This was attributable in part to the presence of a northerly component in the 700-mb. mean anomaly flow for the month.

Most of the Nation's precipitation came in the first half-month when adequate moisture was supplied by southwesterly flow ahead of the western mean trough (fig. 2A). The abrupt change in circulation regime at midmonth brought precipitation to an equally abrupt halt over most of the country. An exception appeared in the Pacific Northwest, where precipitation increased as the mean flow backed from a northwesterly to a southwesterly direction. Additional precipitation occurred in the Southeast during the final week when a mean trough there retrograded sharply in response to the loss of a mean trough in the eastern Pacific (fig. 9B).

5. ALASKA AND HAWAII

Temperatures in southern and central Alaska were above normal because of a southerly component in the flow behind a mean ridge (fig. 1). The flow diminished northward, however, and northern coastal temperatures, already cold in December, remained so in January.

Alaskan precipitation was not far from normal for the month except for an excess over normal of 8.89 inches at Annette. This was the second wettest January on record at Annette and the 18th consecutive month with excessive amounts.

On windward Hawaii, Hilo reported 11.82 inches more rainfall than normal, but Honolulu, a leeward station, reported 4.17 inches less than normal. Lihue, with less pronounced orographic influences, reported a deficit of 5.26 inches. These precipitation totals were in general agreement with the mean circulation, which was slightly anticyclonic and exhibited a weak northerly component in the 700-mb. height anomaly field (fig. 1).

REFERENCES

1. W. H. Klein, "The Weather and Circulation of January 1955—A Month with a Mean Wave of Record Length," *Monthly Weather Review*, vol. 83, No. 1, Jan. 1955, pp. 14–22.
2. C. M. Woffinden, "The Weather and Circulation of December 1959—An Abrupt Change from a Cold Fall Season," *Monthly Weather Review*, vol. 87, No. 12, Dec. 1959, pp. 453–458.
3. J. Namias, "The Index Cycle and Its Role in the General Circulation," *Journal of Meteorology*, vol. 7, No. 2, Apr. 1950, pp. 130–139.
4. J. Namias, "The Annual Course of Month-to-Month Persistence in Climatic Anomalies," *Bulletin of the American Meteorological Society*, vol. 33, No. 7, Sept. 1952, pp. 279–285, and an unpublished extension through 1954.
5. U.S. Weather Bureau, *Climatological Data–National Summary*, vol. 11, No. 1, Jan. 1960.
6. U.S. Weather Bureau, *Weekly Weather and Crop Bulletin, National Summary*, vol. XLVII, No. 4, Jan. 24, 1960; No. 5 Feb. 1, 1960; and No. 6, Feb. 8, 1960.

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